VOLUME LII NUMBER 3

THE JOURNAL OF GEOLOGY

May 1944

SOURCES OF MODERN SANDS IN THE MIDDLE RIO GRANDE VALLEY, NEW MEXICO

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ABSTRACT

In the Middle Rio Grande Valley, New Mexico, serious flood damage, drainage impairment, and soil impoverishment are occurring as a result of the accumulation of modern sediment. The relative importance of various sources of the injurious sediment, which is largely sand, has been determined from the heavy-mineral composition of channel deposits of the Rio Grande and its tributaries. It was found that about 48–54 per cent of the Rio Grande channel and floodway sand deposits between San Acacia and San Marcial have come from the Rio Puerco, 19–21 per cent from the Rio Salado, and 25–33 per cent from the rest of the drainage basin. The Rio Puerco drains about 21 per cent of the watershed, and the Rio Salado about 6 per cent. Of the channel and floodway deposits between Albuquerque and Bernardo, about 21–39 per cent have come from the Rio Jemez, 2–6 per cent from the Rio Galisteo, 0.6–2.0 per cent from Santa Fe Creek, 11–37 per cent from the Rio Grande above Cochiti, New Mexico, and the rest from small tributaries for which separate evaluations were not made.

Tributary contributions to the main stream apparently did not change greatly during the five-year period of investigation, 1937–41. Since 1880, however, there have been marked changes in contribution from some tributaries and in the mineral composition of the Rio Grande sands between San Acacia and San Marcial.

All source evaluations were based on the hydraulic ratios of the heavy minerals. The reasons why other methods of representing mineral compositions are not suitable for source evaluations are outlined.

INTRODUCTION

In the Middle Rio Grande Valley, New Mexico, modern sediment accumulation has been very rapid. From 1936 to 1941 more than 12,000 acre-feet[1] of sediment were deposited annually in the Middle Valley between Cochiti and the head of Elephant Butte Reservoir.[2] Of this, about 9,600 acre-feet (75 per cent) were deposited annually in the 33 miles of valley below San Acacia, New Mexico. About 10,000 of the 12,000 acre-feet accumulated in the river channel, in the floodway, and on those parts of the flood plain that are not protected by levees. This represents an average aggradation of 0.19 foot per year. In the lower 33 miles of the valley the rate of aggradation was 0.33 foot per year.

Such sediment deposits, accumulating over a period of years, have caused much damage. The capacity of the channel and floodways to discharge floodwaters has been reduced, with consequent increase in the frequency and duration of overbank floods. In some places the ground-water table has been raised, and in others extensive areas have been swamped (Fig. 1). Drainage has been impaired; and, in consequence, alkali salts,

[1] An acre-foot is 1 acre covered to a depth of 1 foot (43,560 cubic feet or 1,613 cubic yards).

[2] S. C. Happ, "Modern Sediment Accumulation in the Middle Rio Grande Valley," manuscript in the files of the Sedimentation Section, Soil Conservation Service. Submitted for publication as a *U.S. Dept. Agric. Tech. Bull.*

which might otherwise be removed in the drainage water, cannot be kept below toxic concentrations. Near breaks in the levees, sand splays a foot or more in thickness have covered pastures and cultivated land (Fig. 2). Because sediment accumulation is progressive, these and other types of sediment damage may be expected to increase in the future unless early action is taken to reduce and control the excessive sediment load brought into the Middle Valley.

FIG. 1.—Ponded water in a low area in the Rio Grande Valley near Isleta, N.M. This is one of many formerly cultivated areas on which water has been ponded as a result of river aggradation and associated drainage obstruction.

The drainage basin of the Middle Valley is about 25,000 square miles in area, or roughly half the size of the state of Illinois. To obtain maximum results from sediment control at minimum cost, expenditures must be concentrated in those parts of this large drainage area from which disproportionately large quantities of injurious sediment are derived. This requires, first, determination of the particular type or types of sediment that cause damage and, second, an evaluation of the relative importance of various parts of the drainage basin as sources of the injurious sediment.

In 1936 an investigation of sedimentation in the Middle Valley and of the types and sources of injurious sediment was begun by the Sedimentation Division, Soil Conservation Service. This investigation was continued intermittently through 1941. The volume, distribution, and character of the sediment have been determined by field surveys under the direction of S. C. Happ,[3] and the sources

[3] *Ibid.*

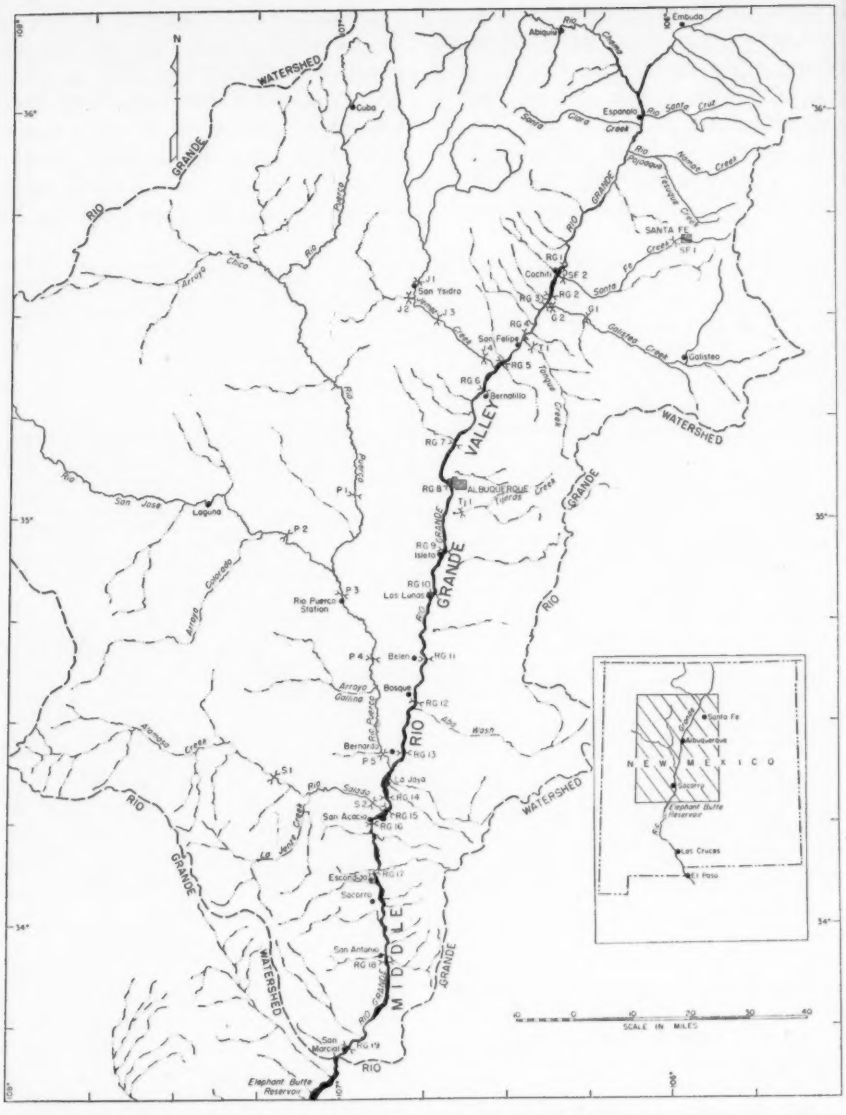
of sand—the most important type of injurious sediment—have been evaluated by the writer through the use of heavy minerals.[4] The results of the source evaluations are presented here. To develop sound methods of evaluating sediment sources with heavy minerals, a critical study of the principles of heavy-mineral transportation and deposition was made.[5] The methods are also applicable in other types of geological investigations.

Using the heavy-mineral method, it has been determined that, between San Acacia and San Marcial (Fig. 3), about 48–54 per cent of the channel and floodway sand deposits in the Rio Grande have come from the drainage basin of the Rio Puerco, 19–21 per cent from the Rio Salado, 4–9 per cent from the Rio Jemez, 0.4–1.4 per cent from the Rio Galisteo, 0.1–0.4 per cent from Santa Fe Creek, 2–8 per cent from the Rio Grande above Cochiti, and 7–26 per cent from tributaries for which separate evaluations were not made. Of the channel and floodway deposits between Albuquerque and Bernardo, New Mexico, about 21–39 per cent have come from the Rio Jemez, 2–6 per cent from the Rio Galisteo, 0.6–2.0 per cent from Santa Fe Creek, 11–37 per

FIG. 2.—Sediment deposits and overflow waters near Bernardo, N.M., due to levee break during flood of May, 1937.

[4] Gordon Rittenhouse, "The Heavy Mineral Method for Evaluation of Sediment Sources," manuscript in the files of the Sedimentation Section, Soil Conservation Service. Submitted for publication as a *U.S. Dept. Agric. Tech. Bull.*

[5] *Ibid.*; "Transportation and Deposition of Heavy Minerals," *Bull. Geol. Soc. Amer.*, Vol. LIV (1943), pp. 1725–80.


Embudo
Rio Santa Cruz
Espanola
Santa Clara Creek
Rio Pojoaque
Nambe Creek
Rio Grande
Tesuque Creek
SANTA FE
Santa Fe Creek
SF 1
RG 1
Cochiti
SF 2
RG 2
G 2
G 1
Galisteo Creek
Galisteo
San Ysidro
J 1
J 2
J 3
Jemez Creek
RG 3
RG 4
San Felipe
T 1
RG 5
RG 6
Bernalillo
Torreon Creek
WATERSHED
RG 7
VALLEY
RG 8
ALBUQUERQUE
Tijeras Creek
T 1 1
GRANDE
Rio Puerco
P 1
Rio San Jose
Laguna
P 2
RG 9
Isleta
RG 10
Los Lunas
RIO
Rio Puerco Station
P 3
Arroyo Chico
Arroyo Galleto
P 4
Belen
RG 11
Arroyo Galina
Bosque
RG 12
Rio Puerco
Abo Wash
Bernardo
RG 13
P 5
Manzano Creek
S 1
La Joya
RG 14
Rio Salado
S 2
San Acacia
RG 15
RG 16
La Joya Creek
Escondido
RG 17
Sacorro
San Antonio
RG 18
MIDDLE
San Marcial
RG 19
Elephant Butte Reservoir
Rio Puerco
Rio Salado
Rio Grande
Arroyo Chico
Rio Puerco
Arroyo Galleto
Arroyo Galina
Manzano Creek
La Joya Creek
Abo Wash
Tijeras Creek
Torreon Creek
Jemez Creek
Santa Fe Creek
Tesuque Creek
Nambe Creek
Rio Pojoaque
Rio Santa Cruz
Santa Clara Creek
Abiquiu Creek
Rio Chama
Rio Grande
Rio Puerco
Rio Salado
Rio San Jose
Arroyo Chico

cent from the Rio Grande above Cochiti, and 16–65 per cent from small tributaries for which separate evaluations were not made. The Rio Salado and Rio Puerco evaluations are based on samples collected in 1937, 1938, 1940, and 1941; those for the Rio Jemez, on samples collected in 1937, 1938, 1939, and 1940; and those for the Rio Galisteo, Santa Fe Creek, and the Rio Grande above Cochiti, on samples collected in 1937 and 1938.

On the basis of contribution per unit of drainage, the Rio Salado delivers about $3\frac{1}{2}$ times, the Rio Puerco about $2\frac{1}{2}$ times, and the Rio Jemez about $1\frac{1}{2}$ times as much sand to the deposits between San Acacia and San Marcial as the average for the entire drainage basin. To the deposits between Albuquerque and Bernardo the Rio Jemez contributes most per unit of drainage area; the Rio Grande above Cochiti contributes least.

AREA OF STUDY

The Rio Grande rises in central southern Colorado, flows southward through central New Mexico to the international boundary, and thence southeast between Texas and Mexico to the Gulf. The Middle Rio Grande Valley, with which this paper is concerned, extends from Cochiti to just below San Marcial in north-central New Mexico, a distance of about 145 miles, as measured along the axis of the valley. Above San Marcial the drainage area is about 24,200 square miles, of which about 11,600 square miles are above Cochiti.

In the Middle Valley the Rio Grande is joined by numerous tributaries. Of these, the most important are Santa Fe Creek and the Rio Galisteo, which rise in the Sangre de Cristo Mountains and flow westward to enter the Rio Grande near Cochiti and San Domingo, respectively; the Rio Jemez, which rises in the Jemez Mountains and flows southeastward to join the Rio Grande above Bernalillo; the Rio Puerco, which rises in and west of the San Pedro Mountains and flows southward to enter the Rio Grande below Bernardo; and the Rio Salado, which rises in the Datil Mountains and flows eastward to join the Rio Grande above San Acacia (Fig. 3).

The physical characteristics and stream flow of the area have been described by C. K. Cooperrider and B. A. Hendricks,[6] by Kirk Bryan and George M. Post,[7] and by others and will be summarized only briefly here. The area has typical basin and range topography with elevations ranging from about 4,200 feet at San Marcial to about 14,000 feet on the highest peaks. In general, the valleys are warm and semiarid, with annual rainfall of 8–10 inches; the mountains are cooler and have from 18 to 34 inches of precipitation, much of which falls as snow. Spring and early summer floods in the Middle Valley usually are caused by rain and melted snow from the mountains; summer floods, from heavy local rains in one or more of the tributary areas; and fall floods, from either local or general storms. All five major tributaries to the Middle Valley are dry or else carry just a few second-feet of water during much of the year.

Since about 1870 many of the tributary stream channels have been deeply trenched and widened. At about that date the Rio Puerco, for example, appears to have had a discontinuous channel, averaging perhaps 10 feet in depth

[6] "Soil Erosion and Stream Flow on Range and Forest Lands of the Upper Rio Grande Watershed in Relation to Land Resources and Human Welfare," *U.S. Dept. Agric. Tech. Bull. 567* (1937).

[7] "Erosion and Control of Silt on the Rio Puerco, New Mexico," *Rept. to Middle Rio Grande Conserv. Dist. Spec. Exhibit R-1* (1928).

and 100 feet in width.[8] Now the channel averages over 20 feet in depth and 300 feet in width for about 150 miles above its mouth. Such trenches are an important source of sediment. The rate of upland erosion has also increased greatly. Some believe that this accelerated erosion has accompanied climatic change,[9] others, that it has resulted from overgrazing and destructive lumbering.[10]

The channel of the Rio Grande has not been trenched and consequently is very different from the channels of many of the tributaries. At low-river stages it is a winding, elongated sand flat, averaging about 200–300 yards in width. One or more small low-water channels meander over the sand flat, re-working the deposits in it. At high stages the entire sand flat, as well as the adjacent floodway area beyond the low banks, is under water. Between large floods the width of the sand flat is decreased by growth of cottonwoods and salt cedars. These may be removed or the entire channel shifted during high flows. Along much of its length in the Middle Valley, levees have been built to confine floodwaters. At some places the floodway is more than half a mile in width.

INJURIOUS SEDIMENT

In the Middle Rio Grande Valley, deposition in the channel and floodway is the direct or indirect cause of nearly all the sediment damage. In the channel more than 90 per cent of the sediment is sand, of which 75 per cent or more is between 0.351 and 0.088 mm. in diameter. In the floodways it is estimated that more than 40 per cent of the sediment is sand, the rest being silt and clay that is interbedded with or overlies the sand. Of the sand in the floodway, about 70 per cent is between 0.351 and 0.088 mm. in diameter. Sand deposition in the channel, by increasing the frequency and duration of overbank flow, appears to have contributed much to the deposition of the silt and clay on the floodway berms. Sand, and more specifically sand between 0.351 and 0.088 mm. in diameter, is the most injurious type of sediment in the Middle Valley.

THE PRINCIPLE OF CONTAMINATION

To use the heavy-mineral composition of sands to locate and quantitatively evaluate source areas, the principle of "contamination" or mixing is employed. Sand brought to a stream by a tributary will contain light and heavy minerals in amounts characteristic of that tributary. The main stream above the tributary will also contain light and heavy minerals in characteristic proportions. Below the junction the mineral composition will depend upon the relative amounts of sand from the tributary and the main stream, that is, on the amount of contamination by the tributary. This principle of contamination has been outlined previously by L. Cayeux[11] and has been applied to heavy minerals by Paul D. Krynine.[12]

[8] Bryan, "Historic Evidence on Changes in the Channel of Rio Puerco, a Tributary of the Rio Grande in New Mexico," *Jour. Geol.*, Vol. XXXV (1928), pp. 265–82.

[9] *Ibid.*

[10] Cooperrider and Hendricks, pp. 22–30 of ftn. 6. (1937).

[11] *Les Roches sedimentaires de France* (Paris, 1929).

[12] "Glacial Sedimentology of the Quinnipiac-Pequabuck Lowland in Southern Connecticut," *Amer. Jour. Sci.*, Vol. XXXIII (5th ser., 1937), pp. 111–39; "Age of Till on Palouse Soil from Washington," *ibid.*, pp. 205–16. In contamination studies using heavy minerals, the weight of heavies from various sources must be considered. In a previous reference to Krynine's work, in which only the first paper was cited (Rittenhouse, p. 1778 of ftn. 5 [1943]), the writer stated: "In Krynine's (1937) use of heavy minerals to evaluate sediment sources it was tacitly assumed that the weight of heavies

The method by which the principle of contamination is used may be illustrated by the simple case shown by Figure 4, in which, for convenience in reference, the tributary has been designated as *A*, the main stream above the junction as *B*, and the main stream below a mixing zone as *C*. Of each 1,000 sand grains in *A*, 3 might be garnet and 997 might be other minerals; and of each 1,000 sand grains in *B*, 21 might be garnet and 979 might be other minerals. Further, if the sand at *C* comes in equal amounts from *A* and *B*, then, of each 1,000 sand grains at *C*, 12 would be garnets and 988 would be other minerals.

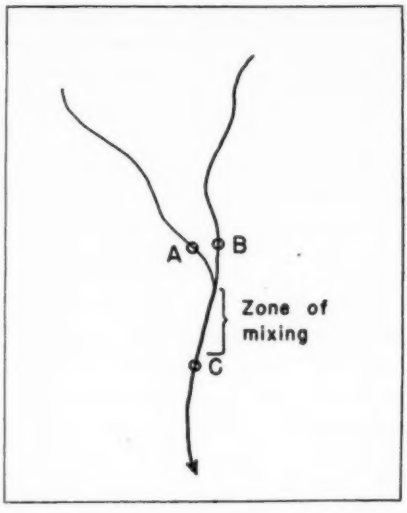


FIG. 4.—Sketch showing position of samples from which contamination may be determined.

From *A*:	3 garnets in 1,000 grains
From *B*:	21 garnets in 1,000 grains
From *A* and *B*:	24 garnets in 2,000 grains
	or
	12 garnets in 1,000 grains

From *A*:	997 others in 1,000 grains
From *B*:	979 others in 1,000 grains
From *A* and *B*:	1,976 others in 2,000 grains
	or
	988 others in 1,000 grains

If *B* contributed twice as much as *A*, of each 1,000 grains at *C*, 15 would be garnets and 985 would be other minerals. Similarly, the mineral composition in *C* could be computed for any combination of quantities from *A* and *B* but could not exceed 21 garnets and 979 others per 1,000 grains if all sand came from *B*, or could not be less than 3 garnets and 997 others per 1,000 if all sand came from *A*.

From *A*:	3 garnets in 1,000 grains
From *B*: 21 × 2	= 42 garnets in 2,000 grains
From *A* and *B*:	45 garnets in 3,000 grains
	or
	15 garnets in 1,000 grains

From *A*:	997 others in 1,000 grains
From *B*: 979 × 2	= 1,958 others in 2,000 grains
From *A* and *B*:	2,955 others in 3,000 grains
	or
	985 others in 1,000 grains

In the example above there were four factors, namely, (1) the mineral composition at *A*, (2) the mineral composition at *B*, (3) the mineral composition at *C*, and (4) the relative amounts of sand con-

from all sources was the same. For most investigations this assumption is not valid." In a personal communication Krynine has pointed out that this assumption was not made and that his concept of differential contamination was expounded not in one paper but in two. The writer takes this opportunity of noting that in the second paper the possibility of different amounts of heavies coming from different sources was presented, discussed, and illustrated.

tributed by A and B. Of these four factors, three were assumed to be known and the fourth was computed. Suppose, however, that the mineral composition in A, B, and C is known but that the relative amounts of sand contributed by A and B are not known. From the three values that are known, the fourth may be computed. For example, assume that the sand in C contains 18 grains of garnet and 982 grains of other minerals per 1,000 grains of sand and that the composition at A and B was the same as in the foregoing example. Let X be equal to the number of 1,000-grain units of sand from B that must be mixed with 1,000 grains of sand from A to give the composition at C.

To have a sand at C containing 18 garnets and 982 other grains in each 1,000, the contribution from B must have been five times that from A. Similarly, if the composition at C had been 9 grains of garnet and 991 grains of other minerals per 1,000 grains, the contribution from B would be only one-half of that from A.

These examples illustrate, in its simplest form, the principle of contamination that has been used to determine the relative amounts of sand derived from various sources. Actually, as will be shown (pp. 153–55), numbers of grains,

From A: 3 garnets in 1,000 grains
From B: $21X$ garnets in $1{,}000X$ grains
From A and B: $3 + 21X$ garnets in $1{,}000 + 1{,}000X$ grains

$$\frac{3 + 21X}{1{,}000\,(1 + X)} = \frac{18}{1{,}000}$$
$$3 + 21X = 18 + 18X$$
$$3X = 15$$
$$X = 5$$

From A: 997 others in 1,000 grains
From B: $979X$ others in $1{,}000X$ grains
From A and B: $997 + 979X$ grains in $1{,}000 + 1{,}000X$ grains

$$\frac{997 + 979X}{1{,}000\,(1 + X)} = \frac{982}{1{,}000}$$
$$997 + 979X = 982 + 982X$$
$$15 = 3X$$
$$5 = X$$

From A: 3 garnets in 1,000 grains
From B: $21X$ garnets in $1{,}000X$ grains
From A and B: $3 + 21X$ garnets in $1{,}000\,(1 + X)$ grains

$$3 + 21X = 9 + 9X$$
$$12X = 6$$
$$X = \tfrac{1}{2}$$

From A: 997 others in 1,000 grains
From B: $979X$ others in $1{,}000X$ grains
From A and B: $997 + 979X$ others in $1{,}000\,(1 + X)$ grains

$$\frac{997 + 979}{1{,}000\,(1 + X)} = \frac{991}{1{,}000}$$
$$997 + 979X = 991 + 991X$$
$$6 = 12X$$
$$\tfrac{1}{2} = X$$

percentages by number, or ratios by number cannot be used to determine contamination. The hydraulic ratio,[13] defined as one hundred times the weight of heavy minerals in a known range of size divided by the weight of light minerals of hydraulic equivalent size, or weight percentages (to a limited extent) must be used.

GENERAL PROCEDURE

For each tributary area for which contribution to the main stream deposits is to be evaluated, sand samples are collected from the bed of the tributary, from the bed of the main stream above the junction, and from the bed of the main stream below the junction. In the laboratory the samples are sized by sieves, and the light and heavy minerals in one or more size grades are separated in a "heavy" liquid. The light- and heavy-mineral fractions from each size grade are weighed, the heavy minerals are mounted for microscopic examination, and the relative abundance of the different species is determined by identifying and counting 300 or more grains.

The frequencies by number are changed to frequencies by weight, using a specific-gravity correction. The weight of each kind of heavy mineral in the size grade is computed. This weight is divided by the weight of light minerals that are of equal hydraulic value, that is, that are transported and deposited with that heavy mineral. The resulting "hydraulic ratio" eliminates most of those differences in mineral composition that accompany differences in texture and sorting of the bed samples. From the hydraulic ratios in the tributary, in the main stream above the junction, and in the main stream below the junction the relative contribution to the main stream below the junction is computed by the method outlined on pages 150–51, except that hydraulic ratios are used instead of the number of grains.

[13] Rittenhouse, ftn. 5 (1943).

HEAVY MINERALS AND CONTAMINATION

Several methods are commonly used for comparing the heavy-mineral composition of streams or geological formations. In all these methods the heavy minerals are separated from the light minerals in a heavy liquid and their relative abundance is estimated, or determined more precisely by identifying and counting 100 or more grains. The frequencies (percentages) by number, or ratios between numbers of selected minerals, are used to compare different samples.[14]

For the quantitative determination of contamination, however, there are several reasons why these and other less commonly used methods are not suitable. First, below the junction of a tributary with a main stream the mineral composition depends not only on the relative frequencies by number of the various heavy minerals in the tributary and main-stream sands but also on the absolute amounts of heavy minerals in the two sands. This may be illustrated by a simple example. Assume that sand *X* carries 10 per cent by weight of heavy minerals, of which half is apatite and half is hornblende. Since both of these minerals have essentially the same specific gravity and shape, the number frequencies would be essentially the same, namely, apatite, 50 per cent; hornblende, 50 per cent. Assume, also, that sand *Y* carries only 2 per cent by weight of heavy minerals, of which one-tenth is apatite and nine-tenths is hornblende. The number frequencies would be apatite, 10 per cent; hornblende, 90 per cent.

[14] W. C. Krumbein and F. J. Pettijohn, *Manual of Sedimentary Petrology* (New York: D. Appleton-Century Co., 1938), pp. 465–89.

A mixture of equal quantities of sands *X* and *Y* would actually yield a sand containing 6 per cent by weight of heavy minerals, of which apatite would be about 43.3 per cent and hornblende would be 56.7 per cent. Yet, if the amounts of *X* and *Y* needed to produce this mixture were computed from the number frequencies alone, the apparent contribution would be about 5 parts of *X* to 1 part of *Y*. If ratios are used, two answers are available, neither of which is correct: the apatite/hornblende ratio, indicating 2.8 parts of *X* to 1 part of *Y;* the hornblende/apatite ratio, indicating 25 parts of *X* to 1 part of *Y*.

Actual differences in percentage by weight between some of the tributary and main-stream sands in the Middle Valley show that the foregoing example is not extreme. For example, the 0.124–0.088 size grade of Rio Salado sample S 2 contained 7.4 per cent of heavy minerals other than magnetite, and the RG 14 sample from above the mouth of Rio Salado contained only 1.4 per cent of heavy minerals other than magnetite. It seems clear that, when contamination is to be determined quantitatively, the absolute abundance, as well as the relative frequency, must be considered.

A second factor is the relation of the heavy-mineral content to the texture and sorting of the deposits in which they occur. R. Dana Russell[15] has given convincing evidence that heavy minerals are concentrated in the finer size grades of sand and that marked differences in mineral composition accompany differences in texture and sorting of sands in the same river. W. W. Rubey[16] has indicated that such concentration and such differences may be due to differences in specific gravity and shape of the light and heavy minerals, to differential availability of various sizes in the source rocks, and to differential wear during downstream transportation. The writer[17] has shown that the size distribution by weight varies systematically with change in texture of the deposits and that, in samples from a transverse cross section of the Rio Grande, number percentages and ratios by number between minerals of different density may differ signficantly. It is believed that the size distribution of any heavy mineral in river deposits is determined by (1) the hydraulic conditions at the place and time of deposition, (2) the hydraulic equivalent size of the heavy minerals, (3) the relative availability of the heavy minerals in the stream load, and (4) some factor or factors, now unknown. For heavies of low density (hornblendes, pyroxenes, etc.) the unknown factors are of minor importance.

In the Middle Valley the texture of the tributary and main-stream channel deposits is not the same; and, consequently, variations in the heavy-mineral content that are associated with the textural differences must be considered. For example, in 1941 the Rio Grande channel deposits at RG 14 (above the Rio Salado) had a median size of 0.163 mm. and a Trask sorting coefficient[18] of 1.36. The same year the median size of the Rio Salado deposits at S 2 was 0.230 mm., and the sorting coefficient was 1.41. Apparent differences in mineral composition due to texture of the channel deposits must be eliminated or corrected to obtain

[15] "The Size Distribution of Minerals in Mississippi River Sands," *Jour. Sed. Pet.*, Vol. VI (1936), pp. 125–42.

[16] "The Size-Distribution of Heavy Minerals within a Water-laid Sandstone," *Jour. Sed. Pet.*, Vol. III (1933), pp. 3–29.

[17] Rittenhouse, ftn. 5.

[18] Parker D. Trask, *Origin and Environment of Source Sediments of Petroleum* (Houston: A.A.P.G., 1932), p. 71.

a satisfactory basis for determining contamination.

The third factor may be even more important. Of primary interest in sand-source investigations is the relative amount of sand of different sizes actually being delivered to the main stream by tributaries. Thus, the interest is in the stream load of the tributaries and the main stream rather than in sand that may be temporarily or permanently deposited in their channels. Consequently, the examination of the bed deposits is helpful only in so far as these bed deposits measure the relative or absolute amounts of debris of different sizes in the stream load or as they furnish data from which such information can be derived.

This raises a point of major importance: Is the texture of channel deposits the same as the texture of the stream load? Or, stated differently, if a continuous record were made of the amount of sediment transported past a sampling station, would the texture of this stream load be the same as the average texture of the channel bed during the same period? For the silt and clay that move downstream as suspended load, the answer to this question clearly is negative for most streams, because little sediment of this size is found in channel deposits. At many shoals and rapids the answer is negative for sands too. Few would argue that the boulders or gravel in the channels at such places represent the average texture of the stream load that passes the shoals or rapids.

For other parts of stream systems the available information on this relationship appears to be contradictory. At the Soil Conservation Service sedimentation station on the Enoree River near Taylors, South Carolina, the sand in the stream load is much finer than the sand in the bed deposits for a mile upstream.[19] During the flood of August, 1939, for example, 0.27 mm. was the median size of all sand coarser than 0.175 mm. passing the station, whereas 0.78 mm. was the median size in the bed deposits (Fig. 5). Because this 1939 flood was one of the highest during the five-year period of record and because in the Enoree River the stream load coarsens with increasing stage, the texture of the stream load would probably be even finer, and the difference between stream load and bed textures even greater, for an extended period of low, medium, and high stages. In contrast, during low stages in Mountain Creek near Taylors the average composition of the bed appears to be about the same as that of the stream load.[20]

In rivers like the Rio Grande a large part of the stream load may be taken into suspension during high stages. In such streams finer particles may be transported downstream faster, on the average, than coarser particles. In contrast, where most of the load is transported by rolling or sliding along the bottom, the coarser particles may outrun the finer.[21] Under either condition, however, the texture of the stream load would not be the same as the texture of the bed deposits. Until the relationship between bed and stream-load texture is understood more fully, the only safe

[19] H. A. Einstein, A. G. Anderson, and Joe Johnson, "A Distinction between Bed-Load and Suspended Load in Natural Streams," *Nat. Res. Coun., Amer. Geophys. Union Trans. of 1940*, Part II (1940), pp. 628–32.

[20] Einstein, personal communication.

[21] Einstein, "Der Geschiebetrieb als Wahrscheinlichkeits Problem," *Mitt. der Versuchsanstalt für Wasserbau an der Eidg. techn. Hochschule in Zurich* (1937); Pang-Yung Ho, "Abhängigkeit der Geschiebebewegung von der Kornform und der Temperatur," *Mitt. preuss. Versuchsanstalt für Wasser-, Erd-, und Schiffbau*, Vol. XXXVII (1939).

assumption is that the texture in the bed and the stream load may not be the same.

The hydraulic-ratio basis of comparing mineral compositions appears to satisfy the three objections to methods in common use, namely: it uses both the frequency and the absolute amounts of heavy minerals, it eliminates apparent differences in mineral composition that are associated with differences in texture of the bed deposits, and it effectively transposes the data from bed samples into usable data on mineral composition in the stream load. As noted elsewhere,[22] weight percentages of heavies may be used to a limited extent. All source evaluations in this paper are based on hydraulic ratios.

[22] Rittenhouse, ftn. 5.

TECHNIQUE

COLLECTION OF SAMPLES

For evaluation of sand sources the Upper Rio Grande drainage basin was divided into subareas, as shown in Table 1.[23] Samples of channel sands were collected at nineteen localities on the main stream and seventeen localities on the tributaries, as indicated in Figure 3. To check on the change in sand contribution with time, collections were made in 1937,

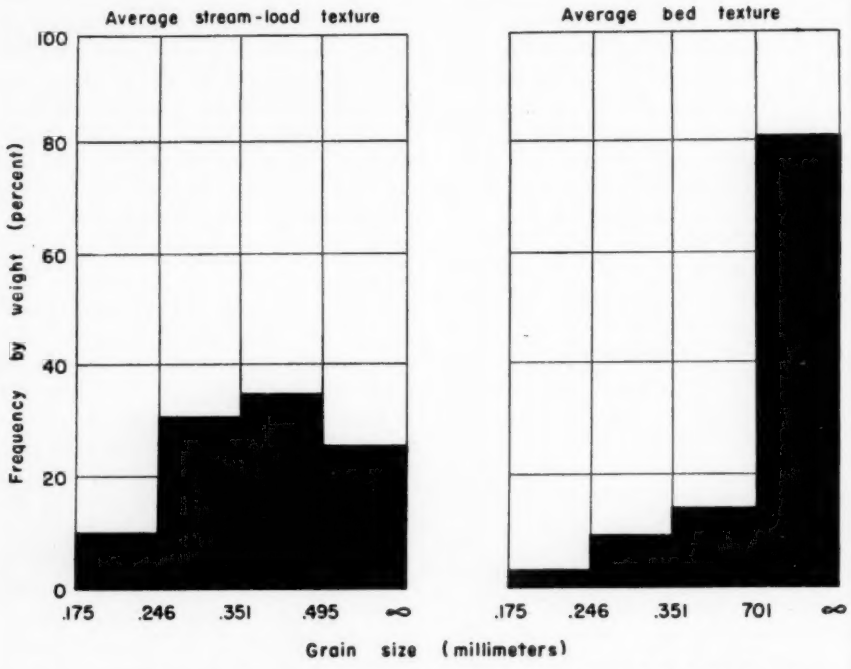


FIG. 5.—Texture of the bed deposits and the stream load in the Enoree River, S.C., during August, 1939

[23] Areas of closed basins have been excluded from Table 1. Data for major tributaries are from Table 193, *Regional Planning*, Part VI: *Upper Rio Grande* (Washington: National Resources Committee, 1938). Data for direct drainage and tributary subareas were determined by planimeter from the base map (Fig. 1) and were adjusted to major tributary areas. All the data appear to be subject to large errors.

1938 (twice), 1939, 1940, and 1941.[24] The collection data are summarized in Table 2.

As a basis for comparing the composition of the modern and premodern sediments, "old sands" that underlie the present flood-plain surface were collected at sixteen localities between Bernalillo and Escondido, New Mexico. To be certain that the old sands near San Antonio were not of local derivation, three samples were collected from the arroyo that enters the valley from the west near that town.

Each of the three general types of local channel conditions that exist in the Rio Grande and its tributaries required a different sampling technique. In many places along the main stream the sediment was below the water surface or so close to the water table that the sand was damp. At these places a coring tube 2 inches in diameter and 44 inches in length was worked about 40 inches into the sediment by hand. The more compact layers were penetrated by alternately raising the coring tube and then forcing it downward. While the tube was still in place, a shovel handle was inserted into the top of the tube to measure the core length. If the core was less than half the penetration, the tube was withdrawn, cleaned, and sunk a foot or so away. The sampler was then withdrawn and the sample transferred to a cloth sack or paper bag, clay or silt layers being removed at this time.

At some places in the Rio Grande channel and in beds of most tributaries the surface sediment was too dry to be penetrated by the coring tube. At such places a hole was dug and the sample collected from a channel down the side. Where the water table prevented excavation to the desired depth, a supplementary coring-tube sample was obtained from the bottom of the hole and combined with the side-wall material to form the spot sample at that place.

Between Cochiti and Bernalillo the bed of the Rio Grande is a cobble pavement overlain by a few inches to about 1 foot of sand. At these localities coring-tube samples of the sand were collected at several closely spaced points and combined to form the spot sample. Since the cobbles were not collected, these samples are deficient in coarse sediment. The wide variation in texture from year to year shown by samples from this part of the river is probably due to sampling technique rather than to natural change.

Samples of old sands were obtained by boring through the surface silts and clays of the flood plain with a 3-inch Iwan soil auger with an extensible handle. The sample was usually composed of sediment from a 1–2-foot vertical section of the test boring. Samples from below the water table were somewhat contaminated by slumping sand and silt from the sides of the hole.

[24] Samples were collected in 1937 by the writer, in 1940 by the writer assisted by Tom Meeks, in 1938 and 1939 by E. H. Moser, Jr., and in 1941 by S. C. Happ. "Old sand" samples also were collected by Dr. Happ.

TABLE 1

AREAS TRIBUTARY TO THE MIDDLE VALLEY

	Square Miles
Rio Grande above Cochiti, N.M.	11,600
Direct drainage—Cochiti to Santa Fe Creek	28
Santa Fe Creek	288
Direct drainage—Santa Fe Creek to Galisteo	124
Rio Galisteo	697
Direct drainage—Galisteo to Jemez	549
Rio Jemez	1,009
Rio Salado Branch	200
Rio Jemez above the Rio Salado Branch	600
Direct drainage—Jemez to Puerco	2,169
Rio Puerco	5,037
Rio San Jose	2,080
Rio Puerco above Rio San Jose	2,715
Direct drainage—Puerco to Salado	257
Rio Salado	1,434
Direct drainage—below Rio Salado	984
Total, Rio Grande above San Marcial	24,176

LABORATORY ANALYSIS

The laboratory technique was varied from year to year and from sample to sample, depending on the availability of a centrifuge for separation of the light and heavy minerals, on the presence or absence of gravel, and on the need for analyzing the spot samples separately.

Experience gained during the analysis of the first samples also suggested desirable modifications in technique that were applied during subsequent analyses. These modifications resulted both in increased accuracy and in savings of time.

The two main procedures followed in the different years are shown by Figure 6. In all, sieve analyses were made on 175 samples, and the heavy minerals were separated from one to seven size grades of 112 of them.[25] The relative frequency by number was determined in the nonmagnetic separates of one or more size grades of 97 samples. About 250,000 grains were identified in the 333 size-grade separates that were examined. On many slides separate counts were made

TABLE 2

SUMMARY OF DATA ON CHANNEL-SAND COLLECTIONS

NUMBER	PLACE	NUMBER OF SPOT SAMPLES COLLECTED					
		Fall 1937	Spring 1938	Fall 1938	Fall 1939	Fall 1940	Summer 1941
RG 1	Cochiti, N.M.	4	.....	4	4	9	.....
RG 2	Above Santa Fe Creek	3	.....	3	3	8	.....
RG 3	Above Rio Galisteo	3	.....	3	3	7	.....
RG 4	San Felipe, N.M.	4	.....	4	3	5	.....
RG 5	Above Rio Jemez	3	.....	3	3	8	.....
RG 6	Bernalillo, N.M.	3	3	6	6	7	.....
RG 7	Alameda, N.M.	5	.....	5	5	.....	.....
RG 8	Albuquerque, N.M.	5	5	6	6	8	.....
RG 9	Isleta, N.M.	4	.....	4	4	7	.....
RG 10	Los Lunas, N.M.	4	4	4	4	7	.....
RG 11	Belen, N.M.	5	.....	5	5	7	.....
RG 12	Bosque, N.M.	4	4	4	4	8	.....
RG 13	Bernardo, N.M.	4	4	4	4	8	4
RG 14	Below La Joya, N.M.	5	.....	5	5	8	4
RG 15	Above Rio Salado	.....	.....	3	3	.....	.....
RG 16	San Acacia, N.M.	4	.....	4	4	8	4
RG 17	Escondido, N.M.	4	4	3	3	8	4
RG 18	San Antonio, N.M.	5	5	5	5	9	.....
RG 19	San Marcial, N.M.	3	.....	3	3	7	.....
SF 1	Santa Fe, N.M.	3	.....	.....	.....	.....	.....
SF 2	Mouth	3	.....	3	3	7	.....
G 1	U.S. Highway No. 85	3	.....	3	3	.....	.....
G 2	Mouth	3	.....	3	3	7	.....
J 1	Railroad crossing	4	.....	4	4	7	.....
J 2	N.M. Highway No. 44	3	.....	3	3	8	.....
J 3	Zia Pueblo	3	.....	3	3	8	.....
J 4	Mouth	3	.....	3	3	8	.....
T 1	U.S. Highway No. 85	3	.....	.....	.....	.....	.....
Tj 1	Albuquerque, N.M.	.....	.....	3	3	.....	.....
P 1	U.S. Highway No. 66	3	.....	3	3	8	.....
P 2	U.S. Highway No. 66	3	.....	3	3	7	.....
P 3	Rio Puerco, N.M.	3	.....	3	3	10	.....
P 4	West of Belen, N.M.	3	.....	2	2	6	.....
P 5	U.S. Highway No. 85	3	.....	3	3	8	4
S 1	Riley, N.M.	3	.....	.....	.....	.....	.....
S 2	U.S. Highway No. 85	3	.....	3	3	8	4

[25] The preliminary reduction in size of the 1937 samples was done by the writer in the Soil Conservation Service laboratory at Albuquerque, N.M. Subsequent laboratory work on many of the 1937 samples, as well as all laboratory work on the 1938 and 1939 samples, was done at the sedimentation

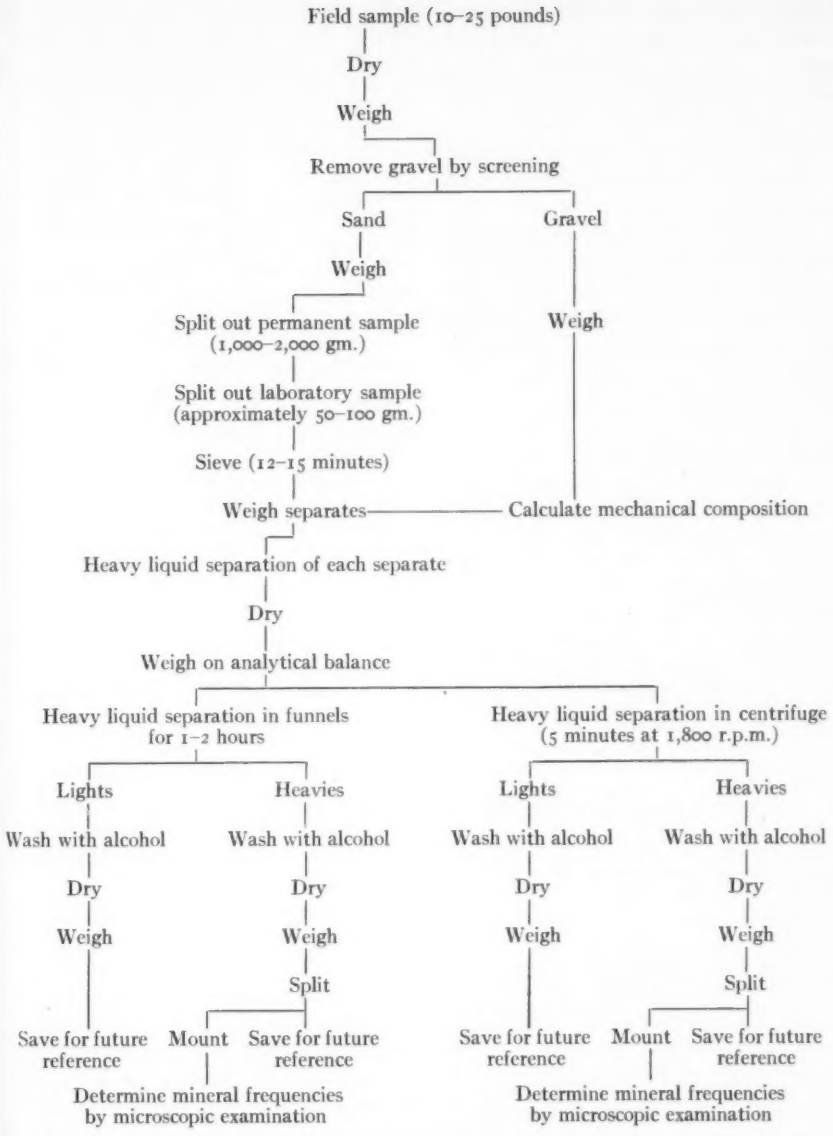


FIG. 6.—Flow sheet for textural and mineralogical analysis of Rio Grande and tributary sands. Samples collected in 1938 and 1939 separated by centrifuge; all others, by gravity settling.

by two or more men. Because the data are so voluminous and will be published in full at a later date,[26] only representative analytical results have been included in this paper (Tables 3, 4, and 5).

The weight of each mineral in each size grade was computed by applying specific-gravity corrections to the number frequencies and then multiplying by the total weight of heavy minerals in the size grade. One hundred times this weight of each heavy was divided by the weight of light minerals of equivalent hydraulic size (Table 6)[27] to give the hydraulic ratio for that mineral.

The calculation of hydraulic ratios may be illustrated by a simplified example. Assume (1) that a test sample weighs 95.0 gm. and has percentages of the sample in various size grades as follows: 0.707–0.500 mm., 2.0 per cent; 0.500–0.354 mm., 10.0 per cent; 0.354–0.250 mm., 22.0 per cent; 0.250–0.177 mm., 32.0 per cent; 0.177–0.125 mm., 22.0 per cent; 0.125–0.088 mm., 10 per cent; and 0.088–0.062 mm., 2 per cent; (2) that the weight of all heavies other than magnetite in the 0.125–0.088-mm. size grade is 0.175 gm. and that the number percentages of hornblende, garnet, and ilmenite are 35, 15, and 50, respectively.

Then the weight of hornblende, garnet, and ilmenite in the 0.125–0.088-mm. size grade are calculated as shown in Table 7.

Next, the size distribution is plotted as a cumulative curve, and the percentage of the sample in size grades $0\,\phi$, $0.1\,\phi$, $0.2\,\phi$, etc., larger than the 0.124–0.088-mm. size grades determined graphically. These percentages are multiplied by the weight of the sample (95.0 gm.) to give the weight of sand that is equivalent in hydraulic size to heavy minerals of the 0.124–0.088-mm. size grade that have hydraulic equivalent sizes of $0\,\phi$, $0.1\,\phi$, $0.2\,\phi$, etc. (Table 8).

For hornblende, which has a hydraulic equivalent size of $0.2\,\phi$, the hydraulic ratio equals $(0.0485 \times 100)/13.0 = 0.373$; for garnet ($0.6\,\phi$) the hydraulic ratio equals $(0.0247 \times 100)/24.1 = 0.102$; and for ilmenite ($0.8\,\phi$) the hydraulic ratio equals $(0.1018 \times 100)/28.5 = 0.357$.

Hydraulic ratios were also computed for hydraulic equivalent sizes up to $0.2\,\phi$ larger and smaller than the size given in Table 6. Representative hydraulic ratios are presented in Table 9.

Contribution from each tributary to its main stream at the first sampling locality below the junction was computed for each mineral in each size grade from the equation $(B - C)/(C - A) = x$, where x is the number of parts of sand from the tributary that must have been mixed with one part of sand from the main stream to give the composition below the junction and where A, B, and C, respectively, are the hydraulic ratios in the tributary, in the main stream above the junction, and in the main stream below the junction.

laboratory, Department of Geology, University of Chicago, which was made available through the courtesy of Dr. F. J. Pettijohn and the University. Some petrographic work on the 1937 samples was done at the Department of Geology, University of North Carolina. All other samples were analyzed in the laboratory of the Sedimentation Division, Soil Conservation Service, at Greenville, S.C. Splitting and sieving of the 1938 and 1939 samples were done by W. E. Bertholf, Jr.; of all other samples, by the writer. Mineral separations of the 1937, 1938, and 1939 samples were made by Bertholf; of all other samples, by the writer. Mineral-frequency counts of the 1937 and 1938 samples were made by B. T. Sandefur, W. A. White, and J. Scott Griffith, assisted by Theodore Lance and Paul Herbert as recorders. Recounts on critical samples of the 1937 and 1938 suite and counts on the 1940 and 1941 samples were made by the writer.

[26] Rittenhouse, ftn. 4.

[27] The hydraulic equivalent size, i.e., the size of light minerals that, on the average, will be transported and deposited with heavy minerals of known size, has been determined by comparing the size-distribution curves of light and heavy minerals from two series of samples from the Rio Grande. See Rittenhouse in ftn. 5. Hydraulic equivalent size is expressed in ϕ units, a measure introduced by W. C. Krumbein ("Application of Logarithmic Moments to Size Frequency Distributions of Sediment," *Jour. Sed. Pet.*, Vol. VI [1936], pp. 35–47). One ϕ is equal to one Wentworth size grade; $0.5\,\phi$, to one $\sqrt{2}$ size grade. For magnetite and ilmenite, $0.8\,\phi$, instead of the $1.0\,\phi$ value given in Table 6, was used. Contributions so determined more nearly checked contributions determined from the low-density minerals.

TABLE 3

MECHANICAL COMPOSITION OF REPRESENTATIVE CHANNEL SANDS, 1937

Sample	Weight of Sample (Gm.)	>0.991 Mm. (Per Cent)	0.991–0.701 Mm. (Per Cent)	0.701–0.495 Mm. (Per Cent)	0.495–0.351 Mm. (Per Cent)	0.351–0.246* Mm. (Per Cent)	0.246–0.175* Mm. (Per Cent)	0.175–0.124 Mm. (Per Cent)	0.124–0.088 Mm. (Per Cent)	0.088–0.061 Mm. (Per Cent)	<0.061 Mm. (Per Cent)	Q_1 (Mm.)	*Md* (Mm.)	Q_3 (Mm.)	*So*†
RG 1.....	58.06	0.3	0.4	0.6	1.5	7.2	18.7	32.0	23.8	8.0	7.6	0.216	0.142	0.103	1.45
RG 2.....	84.42	8.2	3.1	6.0	8.5	14.6	15.8	18.5	13.2	5.1	7.0	0.360	.198	.123	1.71
RG 4.....	77.19	5.8	2.5	6.2	10.7	19.4	19.4	16.9	11.2	3.9	3.8	0.351	.226	.143	1.57
RG 5.....	100.21	2.1	3.5	8.0	13.2	20.2	22.9	19.4	8.1	1.8	0.8	0.360	.240	.161	1.50
RG 6.....	103.70	3.5	2.3	6.5	13.1	25.3	27.0	14.6	5.3	1.3	1.0	0.354	.252	.181	1.40
RG 13.....	62.61	0.2	0.4	2.0	6.0	18.3	23.4	23.9	15.9	5.7	4.4	0.253	.175	.122	1.44
RG 14.....	63.62	0.1	0.3	1.2	3.7	14.3	23.2	25.4	19.0	6.6	6.0	0.224	.161	.115	1.40
RG 16.....	86.81	0.3	0.4	1.6	5.0	16.1	23.0	26.2	16.7	5.1	5.4	0.238	.167	.120	1.41
SF 2.....	94.86	34.0	11.3	16.5	14.5	11.2	4.8	2.9	2.0	1.0	1.9	1.29	.635	.365	1.88
G 2.....	118.94	40.5	6.2	8.4	10.6	13.2	7.3	5.1	4.1	2.0	2.6	1.80	.600	.273	2.56
J 4.....	97.86	4.8	3.0	7.9	14.8	25.8	24.1	14.1	5.8	1.5	0.8	0.380	.267	.189	1.42
P 5.....	60.90	0.1	0.6	2.6	6.4	15.9	17.7	17.5	15.5	6.8	16.8‡	0.250	.155	.093	1.64
S 2.....	95.70	7.6	6.3	9.5	11.4	15.4	10.3	7.6	5.2	1.9	2.8	1.20	0.415	0.222	2.32

* Calibration of sieves showed that the effective opening of the 0.246-mm. sieve was 0.232 mm.

† Sorting coefficient as defined by Trask.

‡ Includes sediment less than 0.061 mm. removed by wet sieving.

TABLE 4

WEIGHT AND PERCENTAGE OF HEAVY MINERALS IN REPRESENTATIVE CHANNEL SANDS, 1937

Sample	Size (Mm.)	Weight (Gm.)	Weight of Light Minerals (Gm.)	Weight of Heavy Minerals (Gm.)	Weight of Magnetite* (Gm.)	Weight of Heavy Minerals Other than Magnetite (Gm.)	Heavy Minerals in Size Grade (Per Cent)
RG 1.....	0.246–0.175	10.832	10.783	0.041	0.005	0.036	0.4
	.175– .124	18.463	18.311	.144	.020	.124	0.8
	.124– .088	13.545	12.971†	.225	.054	.171	1.7
RG 2.....	.246– .175	13.274	13.112	.155	.031	.124	1.2
	.175– .124	15.693	15.403	.284	.065	.219	1.8
	.124– .088	11.166	10.664	.485	.116	.369	4.3
RG 4.....	.246– .175	14.968	14.771	.183	.035	.148	1.2
	.175– .124	13.033	12.733	.297	.074	.223	2.3
	.124– .088	8.616	6.248	.351	.088	.263	4.1
RG 5.....	.246– .175	22.928$_0$	.....	.303$_5$	.064$_0$	.238$_0$	1.3
	.175– .124	19.395$_5$	.....	.431$_0$	.109$_5$	.319$_0$	2.2
	.124– .088	8.049$_0$	.....	.438$_0$	.136$_0$	.301$_5$	5.4
RG 6.....	.246– .175	28.467$_5$	.....	.186$_0$	.029$_0$	.156$_5$	0.7
	.175– .124	15.386$_5$	.....	.260$_0$	.052$_0$	.208$_0$	1.7
	.124– .088	5.556$_0$	.....	.269$_0$	.082$_0$	.185$_5$	4.8
RG 13....	.246– .175	14.619	14.446	.169	.030	.140	1.2
	.175– .124	14.936	14.650	.295	.082	.213	2.0
	.124– .088	9.862	9.467	.389	.098	.291	3.9
RG 14....	.246– .175	14.755	14.680	.087	.005	.082	0.6
	.175– .124	16.144	15.860	.147	.019	.127	0.9
	.124– .088	12.086	11.800	.204	.044	.160	1.7
RG 16....	.246– .175	19.991	19.845	.144	.019	.126	0.7
	.175– .124	22.770	22.485	.290	.036	.254	1.3
	.124– .088	14.510	14.056	.452	.074	.378	3.1
SF 2.....	.246– .175	4.492	4.025	.463	.096	.367	10.3
	.175– .124	2.683	2.105	.579	.152	.427	21.5
	.124– .088	1.920	1.497†	.288	.105	.183	15.0
G 2.....	.246– .175	8.679	8.356	.306	.070	.236	3.5
	.175– .124	6.036	5.726	.318	.083	.235	3.9
	.124– .088	4.796	4.509	.264	.071	.193	5.5
J 4.....	.246– .175	23.530$_0$	.....	.202$_5$	.058$_0$	.143$_0$	0.9
	.175– .124	13.681$_0$	.....	.315$_0$	.131$_0$	.183$_0$	2.3
	.124– .088	5.602$_5$	.....	.320$_0$	.141$_0$	.177$_5$	5.7
P 5.....	.246– .175	10.778	10.668	.106	.011	.095	1.0
	.175– .124	10.570	10.535	.120	.026	.094	1.1
	.124– .088	9.388	9.166	.210	.043	.167	2.2
S 2.....	.246– .175	9.825	9.409	.413	.099	.314	4.2
	.175– .124	7.273	6.771	.467	.097	.370	6.4
	0.124–0.088	4.946	4.409	0.527	0.095	0.432	10.7

* Includes all material attracted by a small horseshoe magnet.

† Part of light mineral fraction lost before weighing.

TABLE 5

Frequency by Number of Heavy Minerals Other than Magnetite in Representative Channel Sands, 1937

Sample	Size Grade	No. of Grains Counted	Percentage							
			Ilmenite§	Zircon	Barite	Garnet	Titanite	Pyroxene	Hypersthene	Diopside (Bronze)‖
RG 1	0.246–0.175	356*	32.3	.....	.....	2.8	0.3	7.3	2.0	.....
	.175– .124	333*	36.0	0.9	0.3	2.1	1.8	5.4	2.1	.....
	.124– .088	756†	40.5	.....	.....	.....	.....	.....	.....	.....
		251	.....	1.4	2.2	2.7	0.8	1.5	0.9	.....
RG 2	.246– .175	665†	47.4	.....	.....	.....	.....	17.4	.....	.....
		61	.....	0.6	0.1	2.5	0.5	.....	0.2	.....
	.175– .124	381*	46.2	0.5	.....	3.9	1.1	6.3	2.6	.....
	.124– .088	906†	50.7	.....	.....	.....	.....	12.2	.....	.....
		165	.....	1.0	0.2	2.0	1.4	.....	0.5	.....
RG 4	.246– .175	1,061†	41.9	0.2	0.1	2.4	1.1	21.4	2.0	.....
	.175– .124	367*	41.0	0.6	.....	3.8	1.1	12.3	2.2	.....
	.124– .088	494†	35.6	.....	.....	.....	.....	13.0	.....	.....
		282	.....	1.1	0.8	1.7	1.7	.....	0.8	.....
RG 5	.250– .175	513‡	10.7	.....	0.2	4.3	1.4	9.0	2.5	0.8
	.175– .124	835‡	13.8	0.2	1.1	2.6	1.2	8.7	1.9	0.6
	.124– .088	738‡	23.3	1.1	0.7	2.2	1.1	6.1	1.0	1.5
RG 6	.250– .175	768‡	4.0	0.3	0.7	1.6	0.4	13.0	1.8	1.3
	.175– .124	709‡	7.9	0.3	0.6	1.1	2.1	7.9	1.8	2.5
	.124– .088	733‡	25.8	2.7	1.4	1.8	1.6	4.6	1.4	1.0
RG 13	.246– .175	464‡	14.4	.....	0.4	1.9	0.4	6.5	2.2	0.7
	.175– .124	452‡	27.7	0.4	0.2	1.6	1.3	9.3	3.1	1.1
	.124– .088	451‡	20.4	1.1	1.8	2.9	1.1	6.0	1.8	0.9
RG 14	.246– .175	339‡	2.1	.....	1.2	.....	1.5	10.6	0.3	0.3
	.175– .124	453‡	7.7	0.9	1.6	2.7	0.4	11.7	1.1	0.7
	.124– .088	808‡	25.7	2.2	3.3	2.6	1.0	6.8	0.7	1.5
RG 16	.246– .175	700‡	4.6	.....	.....	0.1	0.3	14.7	1.4	0.3
	.175– .124	424‡	6.8	.....	0.7	0.5	0.7	11.6	0.5	0.7
	.124– .088	617‡	15.4	0.5	0.8	0.8	0.5	6.5	0.7	1.1
SF 2	.246– .175	354†	37.3	.....	.....	.....	.....	18.6	.....	.....
		87	.....	0.4	.....	1.4	0.5	.....	0.8	.....
	.175– .124	373*	48.3	1.1	0.3	3.8	0.3	5.9	1.3	.....
	.124– .088	291†	35.1	.....	.....	.....	.....	2.4	.....	.....
		87	.....	1.9	0.6	1.9	0.7	.....	0.9	.....
G 2	.246– .175	1,260†	42.5	0.1	0.2	1.1	1.0	26.1	0.6	.....
	.175– .124	273‡	9.2	0.4	0.4	0.4	1.8	11.0	1.5	1.1
	.124– .088	232‡	10.8	.....	0.9	1.3	2.6	6.9	0.4	2.2
J 4	.250– .175	726‡	11.7	.....	1.0	2.1	0.7	13.9	3.6	0.7
	.175– .124	599‡	24.0	0.5	1.2	3.3	1.0	6.8	1.3	1.8
	.124– .088	650‡	42.2	3.2	1.9	2.9	2.3	2.9	0.8	1.4
P 5	.246– .175	347‡	3.8	.....	0.9	0.6	0.6	12.7	0.3	0.6
	.175– .124	932‡	14.2	0.4	4.4	2.5	1.3	11.8	.....	0.9
	.124– .088	613‡	12.6	2.3	1.0	1.1	0.7	4.6	0.5	0.3
S 2	.246– .175	292‡	8.9	.....	0.7	0.3	1.0	22.3	1.4	0.3
	.175– .124	466‡	20.2	0.2	0.9	.....	0.4	12.5	0.6	.....
	0.124–0.088	498‡	20.7	.....	0.6	0.8	0.6	6.8	0.6	0.6

* Counts by B. T. Sandefur. † Counts by W. A. White. ‡ Counts by G. Rittenhouse.

§ At the writer's direction Sandefur and White included all iron ores, other than magnetite, with ilmenite; in the writer's counts other ores are classed as altered grains.

‖ Not separately distinguished from pyroxene by Sandefur and White.

TABLE 5 (*Continued*)

FREQUENCY BY NUMBER OF HEAVY MINERALS OTHER THAN MAGNETITE IN REPRESENTATIVE CHANNEL SANDS, 1937

PERCENTAGE

Diopside (Clear)‖	Blue-Green Hornblende	Green Hornblende	Brown Hornblende	Apatite	Tourmaline	Epidote	Micas	Altered	Rock Fragments	Quartz and Feldspar	Other Minerals¶	Unknowns**
.....	9.0	4.2	1.1	0.6	.....	5.6	16.6	4.2	10.7	.....	.....	3.4
.....	9.9	3.9	3.6	2.1	0.3	2.7	10.5	8.4	6.0	.....	.....	3.9
.....	5.0	3.7	5.2	.....	.....	.....	0.7	7.4	4.9	2.7	27.1	3.0
.....	.....	.....	.....	1.2	1.4	6.4	.....	.....	.....	.....	.....	8.7
.....	5.7	1.5	1.8	.....	.....	.....	3.5	5.9	4.1	1.5	6.9	4.4
.....	.....	.....	.....	0.6	0.1	0.5	.....	.....	.....	.....	.....	2.0
.....	11.0	4.2	1.8	0.5	.....	5.0	6.8	2.9	5.0	.....	.....	2.2
.....	7.8	2.3	2.1	.....	.....	.....	2.5	1.7	4.2	2.1	9.3	5.0
.....	.....	.....	.....	1.0	0.5	1.1	.....	.....	.....	0.1	.....	1.6
.....	4.2	1.1	1.1	0.2	0.1	0.6	0.4	2.5	0.1	0.5	.....	20.2
.....	10.1	6.8	3.6	0.8	0.3	4.9	3.6	3.6	4.1	.....	.....	1.7
.....	15.0	2.6	1.6	.....	.....	.....	1.8	1.4	.....	1.0	10.7	17.2
.....	.....	.....	.....	1.6	0.5	1.5	.....	.....	.....	.....	.....	0.9
0.4	11.7	5.3	1.6	0.6	0.2	8.8	2.9	24.2	11.1	.....	.....	4.5
0.7	12.7	4.4	1.4	1.7	0.6	6.8	2.0	25.9	8.4	.....	.....	5.1
0.5	12.7	5.2	3.4	1.1	0.8	7.7	0.6	17.9	6.8	0.4	.....	6.1
0.8	12.8	4.6	2.2	0.4	0.3	10.0	1.4	28.0	10.4	0.1	.....	6.0
0.4	10.6	6.8	1.3	1.0	0.9	12.0	2.7	26.2	7.5	0.4	.....	6.2
0.6	8.1	4.8	2.5	2.1	1.2	9.7	0.7	16.6	6.7	0.3	.....	6.7
.....	6.0	4.1	2.2	1.1	.....	4.1	14.2	21.6	13.8	3.7	.....	2.8
1.3	9.3	6.0	2.4	0.2	0.7	6.6	2.0	11.7	10.4	1.3	.....	3.2
1.1	8.9	5.8	2.9	0.9	1.3	8.4	2.2	15.7	10.6	1.8	.....	4.4
.....	4.1	4.1	1.2	0.6	0.6	3.2	4.1	49.9	10.0	3.2	.....	2.9
0.7	4.9	4.6	2.4	0.4	1.1	5.5	1.5	36.0	10.2	2.4	.....	3.5
0.7	5.8	4.8	2.7	1.1	1.1	5.0	0.8	17.7	7.9	4.3	.....	4.1
1.3	2.8	7.2	8.2	0.1	.....	2.1	1.9	39.3	12.6	1.1	.....	1.9
0.9	4.0	11.6	6.8	0.5	.....	4.5	0.9	25.5	14.6	7.8	.....	1.4
0.3	2.3	13.6	8.6	1.5	1.0	2.9	1.1	19.8	8.3	12.6	.....	1.8
.....	18.6	2.8	0.3	.....	.....	.....	0.6	16.7	.....	0.6	4.0	0.6
.....	.....	.....	.....	0.1	.....	0.5	.....	.....	.....	.....	.....	0.4
.....	25.2	3.5	1.3	0.3	.....	4.8	0.5	0.3	3.2	.....	.....	.....
.....	29.2	6.2	2.4	.....	.....	.....	0.7	2.4	4.1	1.0	16.2	0.3
.....	.....	.....	.....	0.4	.....	5.2	.....	.....	.....	.....	.....	4.0
.....	5.6	1.1	0.1	0.2	.....	0.2	0.2	19.5	0.3	0.4	.....	1.0
1.1	15.8	8.1	1.8	1.1	1.1	2.6	.....	18.3	9.2	11.4	.....	4.0
1.7	15.1	11.2	3.5	0.9	2.2	8.2	0.4	19.8	4.3	2.2	.....	3.4
0.6	2.3	2.5	1.4	0.6	1.0	6.6	0.8	36.1	9.8	0.7	.....	4.2
0.3	3.3	2.5	0.7	0.8	1.8	10.0	0.2	28.6	6.7	0.8	.....	4.2
0.2	1.1	1.7	0.8	1.4	1.9	7.7	0.5	17.5	3.7	1.7	.....	4.5
0.3	3.2	2.0	0.3	.....	0.3	3.8	3.2	51.0	12.4	1.4	.....	2.9
0.5	4.9	3.5	2.6	0.5	0.5	5.6	0.4	32.0	8.7	1.0	.....	4.2
0.5	3.8	3.1	1.6	1.0	0.7	3.6	4.6	32.5	8.5	5.2	.....	12.2
0.3	1.4	8.6	7.5	.....	0.7	3.4	1.0	29.1	7.5	2.4	.....	3.0
1.3	1.3	12.9	13.7	0.4	0.4	2.2	0.2	22.1	7.9	0.2	.....	2.6
0.8	0.6	13.5	14.7	0.8	0.2	1.0	0.8	10.6	10.0	11.0	.....	5.4

¶ Where a figure appears in this column, two counts were made, so that the abundance of the rarer minerals could be determined more accurately. In the first count, all minerals were identified and the percentage of the rarer minerals as a group computed. The count was then continued for the rarer minerals only, and their abundance was then calculated (Rittenhouse, "The Heavy Mineral Method for Evaluation of Sediment Sources [unpublished manuscript]).

** Unknowns include small quantities of such minerals as zoisite, sillimanite, andalusite, rutile, and topaz.

Naturally, the contributions as determined for different minerals were not exactly the same. In addition, the data for all minerals were not of equal acceptability, for two reasons, namely, (1) at any locality the sampling errors for abundant minerals are smaller than those for rare minerals and (2) contribution could be determined more accurately from minerals that varied greatly in amount in the tributary and main stream than for minerals that were present in about the same proportion. Therefore, instead of using the arithmetic average to best approximate the actual contribution, a weighted average was used wherever the data justified it. To obtain this weighted average, the contribution, as determined for each mineral, was given a weight inversely proportional to the square of its sampling error. These sampling errors were determined from the number percentages and total grain counts and corrected for unexplained variation.[28] Such weighted averages were obtained for the Rio Salado, Rio Puerco, and Rio Jemez. This weighting method is not suitable for tributaries that deliver very little sediment to the main stream. Consequently, arithmetic averages were used to determine the Rio Galisteo and Santa Fe Creek contributions.

The contribution of each subarea to the main-stream deposits between San Acacia and San Marcial and between Bernalillo and Bernardo was then computed.

TEXTURE OF THE CHANNEL DEPOSITS

In the upper part of the Middle Valley the Rio Grande channel deposits consist of fine to medium sands overlying a bed pavement of cobbles and pebbles. Downstream the gravel becomes less abundant and below Albuquerque seldom constitutes more than a few per cent in the upper 5 feet of the deposits. Below Albuquerque, however, the median size of sediment continues to decrease downstream. As shown by Figure 7, this decrease in size may be exponential, although this is by no means certain from the available data. The fluctuations from year to year at the same localities are greater than downstream change between localities.

[28] Rittenhouse, ftn. 5 (1943).

TABLE 6

HYDRAULIC EQUIVALENT SIZES OF VARIOUS HEAVY MINERALS, AS DETERMINED EXPERIMENTALLLY FROM BED SAMPLES AT RG 12 AND TRANSIT SAMPLES AT RG 17*

Mineral	Specific Gravity	Hydraulic Equivalent Size in ϕ units†
Magnetite	5.2	1.0
Ilmenite	4.7	1.0
Zircon	4.6	0.9
Barite	4.5	0.5
Garnet	3.8	0.6
Kyanite	3.6	0.3
Titanite	3.5	0.5
Pyroxene	3.4	0.3
Hypersthene	3.4	0.4
Diopside (bronze)	3.4	0.3
Diopside (clear)	3.3	0.4
Blue-green hornblende	3.2	0.2
Green hornblende	3.2	0.2
Brown hornblende	3.2	0.2
Apatite	3.2	0.4
Tourmaline	3.1	0.2

* From Rittenhouse, "Transportation and Deposition of Heavy Minerals," *Bull. Geol. Soc. Amer.*, Vol. LIV (1943), pp. 1725–80.

† See ftn. 27.

Of the five major tributaries joining the Rio Grande in the Middle Valley, the bed deposits of three—namely, Santa Fe Creek, Rio Galisteo, and Rio Salado—are notably coarser in texture and have poorer sorting than the bed deposits of the main stream near their junctions. The texture of the Rio Jemez and the Rio Puerco sediment is about the same as that of the main stream. Although

Santa Fe Creek and Rio Galisteo appear to have a marked effect in coarsening the Rio Grande bed deposits below their junctions, this effect may be more apparent than real because of the difficulties of sampling in this part of the river. The Rio Salado apparently has little effect on the texture of the Rio Grande deposits below its junction.

Between RG 16 and RG 19, where sediment damage has been most severe, about 83 per cent of the bed deposits are sand between 0.351 and 0.088 mm. in diameter. Between RG 8 and RG 13, where the greatest future damage may occur, about 79 per cent of the bed deposits are of this size. Test borings in the floodways and in the modern deposits of the flood plain indicate that most of the sand is between 0.351 and 0.088 mm. in diameter.

TABLE 7

SAMPLE COMPUTATION, NUMBER FREQUENCY TO WEIGHT IN SIZE GRADE

Mineral	Number Frequency (F) (Per Cent)	Specific Gravity (Spg)	F × Spg	Weight Frequency (Per Cent)	Weight of Each Heavy Mineral in Size Grade (Gm.)
Hornblende	35.0	3.2	112.0	27.7	0.0485
Garnet	15.0	3.8	57.0	14.1	.0247
Ilmenite	50.0	4.7	235.0	58.2	0.1018
Total	100.0		404.0	100.0	0.1750

TABLE 8

SAMPLE COMPUTATION, HYDRAULIC EQUIVALENT WEIGHTS

ϕ	Cumulative Percentage (Finer) than Size-Grade Limits		(3) Percentage in Size Grade (1)−(2)	(4) Weight in Size Grade (3)×95.0
	(1) Upper	(2) Lower		
0	12.0	2.0	10.0	9.5
0.1	15.0	3.5	11.5	10.9
0.2	18.9	5.2	13.7	13.0
0.3	23.2	7.1	16.1	15.3
0.4	28.3	9.3	19.0	18.1
0.5	34.0	12.0	22.0	20.9
0.6	40.4	15.0	25.4	24.1
0.7	46.8	18.9	27.9	26.5
0.8	53.2	23.2	30.0	28.5
0.9	59.6	28.3	31.3	29.7
1.0	66.0	34.0	32.0	30.4
1.1	71.7	40.4	31.3	29.7
1.2	76.8	46.8	30.0	28.5

MINERALOGY OF THE CHANNEL DEPOSITS

KINDS OF MINERALS PRESENT

In the Rio Grande and its tributaries twenty-seven species and varieties of heavy minerals have been identified. Probably other species are present in very small amounts. With few exceptions the same kinds of heavy minerals occur in all samples, but their absolute and relative proportions differ in the various tributaries and in different parts of the main stream. The most abundant heavy minerals are magnetite, ilmenite, pyroxenes, epidote, and hornblende. Also abundant are rock fragments, which are usually composed of both heavy and light minerals and of "altered" grains. Such abundant minerals form 70 per cent or more of most heavy-mineral separates.

Common in nearly all samples, but individually constituting between 0.5 and 5.0 per cent of the nonmagnetic heavy-

HYDRAULIC RATIOS OF SELECTED HEAVY MINERALS IN REPRESENTATIVE CHANNEL SANDS, 1937

Sample	Size Grade	Magnetite (0.8 φ)§	Ilmenite (0.8 φ)	Zircon (0.9 φ)	Barite (0.5 φ)	Garnet (0.6 φ)	Titanite (0.5 φ)	Pyroxene (0.3 φ)	Hypersthene (0.4 φ)	Diopside (Bronze) (0.3 φ)	Diopside (Clear) (0.4 φ)	Blue-Green Hornblende (0.2 φ)	Green Hornblende (0.2 φ)	Brown Hornblende (0.2 φ)	Apatite (0.4 φ)	Tourmaline (0.2 φ)
RG 1	0.246–0.175*	0.333	0.913	.....	.....	0.029	0.003	0.035	0.015	.....	.....	0.041	0.019	0.005	0.004	.....
	.175– .124*	0.377	0.966	0.028	0.005	.029	.024	0.040	.020	.....	.....	0.070	.027	.025	.019	0.002
RG 2	.124– .088†	0.409	0.575	.023	.027	0.27	.007	0.014	.008	.....	.....	0.043	.032	.044	.010	.011
	.246– .175†	0.370	0.770	.011	.002	.027	.004	0.171	.002	.....	.....	0.053	.014	.017	.005	.001
	.175– .124*	0.511	0.890	.012	.....	.066	.018	0.083	.039	.....	.....	0.137	.052	.023	.007	.....
RG 4	.124– .088†	0.846	1.50	.035	.006	.045	.031	0.307	.010	.....	.....	0.185	.055	.050	.022	.010
	.246– .175†	0.354	0.684	.004	.002	.025	.012	0.193	.018	.....	.....	0.036	.010	.010	.002	.001
	.175– .124*	0.490	0.677	.011	.....	.056	.016	0.186	.031	.....	.....	0.144	.097	.051	.011	.004
RG 5	.124– .088†	0.602	0.714	.026	.019	.031	.032	0.288	.015	.....	.....	0.313	.055	.034	.029	.011
	.250– .175‡	0.388	0.214	.....	.003	.058	.016	0.092	.027	0.008	0.004	0.113	.051	.015	.006	.002
	.175– .124‡	0.472	0.258	.005	.019	.039	.017	0.124	.026	.009	.010	0.178	.062	.020	.022	.008
RG 6	.124– .088‡	0.645	0.432	.019	.014	.035	.017	0.113	.016	.028	.009	0.259	.105	.069	.017	.016
	.250– .175‡	0.145	0.045	.004	.005	.011	.002	0.073	.010	.007	.004	0.066	.024	.011	.002	.001
	.175– .124‡	0.181	0.080	.003	.006	.009	.016	0.065	.014	.021	.003	0.092	.059	.011	.007	.007
RG 13	.124– .088‡	0.337	0.250	.024	.021	.018	.019	0.081	.019	.016	.007	0.159	.094	.048	.027	.023
	.246– .175‡	0.639	0.621	.....	.008	.044	.006	0.074	.029	.008	.....	0.058	.039	.021	.013	.....
	.175– .124‡	0.675	0.627	.012	.003	.024	.017	0.122	.040	.014	.017	0.115	.074	.030	.003	.008
RG 14	.124– .088‡	0.547	0.437	.024	.037	.051	.018	0.113	.030	.017	.018	0.177	.115	.057	.014	.026
	.246– .175‡	0.148	0.074	.....	.020	.....	.018	0.084	.003	.002	.....	0.026	.026	.007	.005	.003
	.175– .124‡	0.190	0.138	.017	.017	.027	.003	0.092	.008	.005	.005	0.036	.034	.024	.003	.008
RG 16	.124– .088‡	0.230	0.276	.024	.034	.023	.008	0.061	.006	.020	.006	0.053	.044	.025	.009	.010
	.246– .175‡	0.322	0.140	.....	.....	.002	.003	0.127	.013	.003	.012	0.019	.052	.059	.001	.....
	.175– .124‡	0.251	0.173	.....	.012	.008	.009	0.136	.005	.009	.011	0.043	.124	.074	.006	.....
SF 2	.124– .088‡	0.281	0.307	.010	.015	.012	.007	0.110	.010	.019	.004	0.041	.244	.154	.021	.017
	.246– .175†	0.721	1.16	.014	.....	.044	.016	1.01	.032	.....	.....	0.951	.145	.014	.002	.....
	.175– .124*	1.77	2.64	.069	.025	.270	.019	0.738	.104	.....	.....	2.96	.409	.156	.020	.....
G 2	.124– .088†	2.76	1.91	.118	.046	.121	.046	0.183	.061	.....	.....	2.10	.443	.174	.023	.....
	.246– .175†	0.490	0.778	.001	.005	.016	.016	0.528	.009	.....	.....	0.107	.021	.002	.002	.....
	.175– .124‡	0.622	0.309	.012	.015	.012	.056	0.402	.049	.037	.040	0.567	.289	.065	.034	.039
J 4	.124– .088‡	0.665	0.268	.....	.027	.030	.063	0.190	.010	.053	.046	0.433	.322	.099	.019	.061
	.250– .175‡	0.287	0.113	.....	.007	.013	.004	0.076	.019	.004	.003	0.012	.013	.007	.003	.005
	.175– .124‡	0.510	0.221	.005	.011	.026	.008	0.057	.010	.015	.002	0.029	.022	.006	.006	.016
P 5	.124– .088‡	0.720	0.454	.032	.028	.032	.027	0.046	.010	.021	.002	0.019	.028	.013	.017	.031
	.246– .175‡	0.241	0.111	.....	.015	.009	.008	0.128	.003	.006	.003	0.027	.017	.002	.....	.002
	.175– .124‡	0.269	0.183	.006	.046	.022	.010	0.097	.....	.007	.004	0.039	.028	.020	.004	.004
S 2	.124– .088‡	0.332	0.228	.040	.017	.017	.008	0.066	.006	.005	.006	0.054	.046	.024	.013	.009
	.246– .175‡	0.835	0.328	.....	.025	.009	.027	0.624	.036	.010	.008	0.038	.243	.213	.....	.018
	.175– .124‡	0.845	0.867	0.008	.039	.....	.015	0.478	.023	.....	.044	0.049	.495	.528	.029	.016
	0.124–0.088‡	0.855	1.09	.....	0.039	0.030	0.029	0.403	0.032	0.031	0.042	0.037	0.838	0.912	0.041	0.012

* Based on counts by B. T. Sandefur. † Based on counts by W. A. White. ‡ Based on counts by G. Rittenhouse.

§ Hydraulic ratios for Rittenhouse data based on more precise calibration of sieves and smaller hydraulic-equivalent size intervals than the hydraulic ratios for Sandefur and White data.

Santa Fe Creek and Rio Galisteo appear to have a marked effect in coarsening the Rio Grande bed deposits below their junctions, this effect may be more apparent than real because of the difficulties of sampling in this part of the river. The Rio Salado apparently has little effect on the texture of the Rio Grande deposits below its junction.

Between RG 16 and RG 19, where sediment damage has been most severe, about 83 per cent of the bed deposits are sand between 0.351 and 0.088 mm. in diameter. Between RG 8 and RG 13, where the greatest future damage may occur, about 79 per cent of the bed deposits are of this size. Test borings in the floodways and in the modern deposits of the flood plain indicate that most of the sand is between 0.351 and 0.088 mm. in diameter.

TABLE 7

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Garnet	15.0	3.8	57.0	14.1	.0247
Ilmenite	50.0	4.7	235.0	58.2	0.1018
Total	100.0		404.0	100.0	0.1750

TABLE 8

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ϕ	Cumulative Percentage (Finer) than Size-Grade Limits		(3) Percentage in Size Grade (1)−(2)	(4) Weight in Size Grade (3)×95.0
	(1) Upper	(2) Lower		
0	12.0	2.0	10.0	9.5
0.1	15.0	3.5	11.5	10.9
0.2	18.9	5.2	13.7	13.0
0.3	23.2	7.1	16.1	15.3
0.4	28.3	9.3	19.0	18.1
0.5	34.0	12.0	22.0	20.9
0.6	40.4	15.0	25.4	24.1
0.7	46.8	18.9	27.9	26.5
0.8	53.2	23.2	30.0	28.5
0.9	59.6	28.3	31.3	29.7
1.0	66.0	34.0	32.0	30.4
1.1	71.7	40.4	31.3	29.7
1.2	76.8	46.8	30.0	28.5

MINERALOGY OF THE CHANNEL DEPOSITS

KINDS OF MINERALS PRESENT

In the Rio Grande and its tributaries twenty-seven species and varieties of heavy minerals have been identified. Probably other species are present in very small amounts. With few exceptions the same kinds of heavy minerals occur in all samples, but their absolute and relative proportions differ in the various tributaries and in different parts of the main stream. The most abundant heavy minerals are magnetite, ilmenite, pyroxenes, epidote, and hornblende. Also abundant are rock fragments, which are usually composed of both heavy and light minerals and of "altered" grains. Such abundant minerals form 70 per cent or more of most heavy-mineral separates.

Common in nearly all samples, but individually constituting between 0.5 and 5.0 per cent of the nonmagnetic heavy-

HYDRAULIC RATIOS OF SELECTED HEAVY MINERALS IN REPRESENTATIVE CHANNEL SANDS, 1937

Sample	Size Grade	Magnetite (0.8 φ)§	Ilmenite (0.8 φ)	Zircon (0.9 φ)	Barite (0.5 φ)	Garnet (0.6 φ)	Titanite (0.5 φ)	Pyroxene (0.3 φ)	Hypersthene (0.4 φ)	Diopside (Bronze) (0.3 φ)	Diopside (Clear) (0.4 φ)	Blue-Green Hornblende (0.2 φ)	Green Hornblende (0.2 φ)	Brown Hornblende (0.2 φ)	Apatite (0.4 φ)	Tourmaline (0.2 φ)
RG 1.....	0.246–0.175*	0.333	0.913	.....	.....	0.029	0.003	0.035	0.015	.....	.....	0.041	0.019	0.005	0.004	.....
	.175– .124*	0.377	0.966	0.028	0.005	.029	.024	0.040	.020	.....	.....	0.070	.027	.025	.019	0.002
	.124– .088†	0.409	0.575	.023	.027	0.27	.007	0.014	.008	.....	.....	0.043	.032	.044	.010	.011
RG 2.....	.246– .175†	0.370	0.770	.011	.002	.027	.004	0.171	.002	.....	.....	0.053	.014	.017	.005	.001
	.175– .124*	0.511	0.890	.012	.....	.066	.018	0.083	.039	.....	.....	0.137	.052	.023	.007	.....
	.124– .088†	0.846	1.50	.035	.006	.045	.031	0.307	.010	.....	.....	0.185	.055	.050	.022	.010
RG 4.....	.246– .175†	0.354	0.684	.004	.002	.025	.012	0.193	.018	.....	.....	0.036	.010	.010	.002	.001
	.175– .124*	0.490	0.677	.011	.....	.056	.016	0.186	.031	.....	.....	0.144	.097	.051	.011	.004
	.124– .088†	0.602	0.714	.026	.019	.031	.032	0.288	.015	.....	.....	0.313	.055	.034	.029	.011
RG 5.....	.250– .175‡	0.388	0.214	.....	.003	.058	.016	0.092	.027	0.008	0.004	0.113	.051	.015	.006	.002
	.175– .124‡	0.472	0.258	.005	.019	.039	.017	0.124	.026	.009	.010	0.178	.062	.020	.022	.008
	.124– .088‡	0.645	0.432	.019	.014	.035	.017	0.113	.016	.028	.009	0.259	.105	.069	.017	.016
RG 6.....	.250– .175‡	0.145	0.045	.004	.005	.011	.002	0.073	.010	.007	.004	0.066	.024	.011	.002	.001
	.175– .124‡	0.181	0.080	.003	.006	.009	.016	0.065	.014	.021	.003	0.092	.059	.011	.007	.007
	.124– .088‡	0.337	0.250	.024	.021	.018	.019	0.081	.019	.016	.007	0.159	.094	.048	.027	.023
RG 13.....	.246– .175‡	0.639	0.621	.....	.008	.044	.006	0.074	.029	.008	.....	0.058	.039	.021	.013	.....
	.175– .124‡	0.675	0.627	.012	.003	.024	.017	0.122	.040	.014	.017	0.115	.074	.030	.003	.008
	.124– .088‡	0.547	0.437	.024	.037	.051	.018	0.113	.030	.017	.018	0.177	.115	.057	.014	.026
RG 14.....	.246– .175‡	0.148	0.074	.....	.020	.....	.018	0.084	.003	.002	.....	0.026	.026	.007	.005	.003
	.175– .124‡	0.190	0.138	.017	.017	.027	.003	0.092	.008	.005	.005	0.036	.034	.024	.003	.008
	.124– .088‡	0.230	0.276	.024	.034	.023	.008	0.061	.006	.020	.006	0.053	.044	.025	.009	.010
RG 16.....	.246– .175‡	0.322	0.140	.....	.....	.002	.003	0.127	.013	.003	.012	0.019	.052	.059	.001	.....
	.175– .124‡	0.251	0.173	.....	.012	.008	.009	0.136	.005	.009	.011	0.043	.124	.074	.006	.....
	.124– .088‡	0.281	0.307	.010	.015	.012	.007	0.110	.010	.019	.004	0.041	.244	.154	.021	.017
SF 2.....	.246– .175†	0.721	1.16	.014	.....	.044	.016	1.01	.032	.....	.....	0.951	.145	.014	.002	.....
	.175– .124*	1.77	2.64	.069	.025	.270	.019	0.738	.104	.....	.....	2.96	.409	.156	.020	.....
	.124– .088†	2.76	1.91	.118	.046	.121	.046	0.183	.061	.....	.....	2.10	.443	.174	.023	.....
G 2.....	.246– .175†	0.490	0.778	.001	.005	.016	.016	0.528	.009	.....	.....	0.107	.021	.002	.002	.....
	.175– .124‡	0.622	0.309	.012	.015	.012	.056	0.402	.049	.037	.040	0.567	.289	.065	.034	.039
	.124– .088‡	0.665	0.268	.....	.027	.030	.063	0.190	.010	.053	.046	0.433	.322	.099	.019	.061
J 4.....	.250– .175‡	0.287	0.113	.....	.007	.013	.004	0.076	.019	.004	.003	0.012	.013	.007	.003	.005
	.175– .124‡	0.510	0.221	.005	.011	.026	.008	0.057	.010	.015	.002	0.029	.022	.006	.006	.016
	.124– .088‡	0.720	0.454	.032	.028	.032	.027	0.046	.010	.021	.002	0.019	.028	.013	.017	.031
P 5.....	.246– .175‡	0.241	0.111	.....	.015	.009	.008	0.128	.003	.006	.003	0.027	.017	.002	.....	.002
	.175– .124‡	0.269	0.183	.006	.046	.022	.010	0.097	.....	.007	.004	0.039	.028	.020	.004	.004
	.124– .088‡	0.332	0.228	.040	.017	.017	.008	0.066	.006	.005	.006	0.054	.046	.024	.013	.009
S 2.....	.246– .175‡	0.835	0.328	.....	.025	.009	.027	0.624	.036	.010	.008	0.038	.243	.213	.....	.018
	.175– .124‡	0.845	0.867	0.008	.039	.....	.015	0.478	.023	.....	.044	0.049	.495	.528	.029	.016
	0.124–0.088‡	0.855	1.09	.....	0.039	0.030	0.029	0.403	0.032	0.031	0.042	0.037	0.838	0.912	0.041	0.012

* Based on counts by B. T. Sandefur. † Based on counts by W. A. White. ‡ Based on counts by G. Rittenhouse.

§ Hydraulic ratios for Rittenhouse data based on more precise calibration of sieves and smaller hydraulic-equivalent size intervals than the hydraulic ratios for Sandefur and White data.

mineral fractions, are tourmaline, apatite, garnet, titanite, zircon, and barite. Rare minerals include staurolite, monazite, kyanite, zoisite, sillimanite, andalusite, rutile, topaz, spinel, olivine, and others whose positive identification was not attempted. In addition, varying in color and optical and physical properties. The proportions of hypersthene (and enstatite) and two varieties of diopside were separately recorded, but all other pyroxenes were grouped together. Small quantities of tremolite were included with the pyroxenes, be-

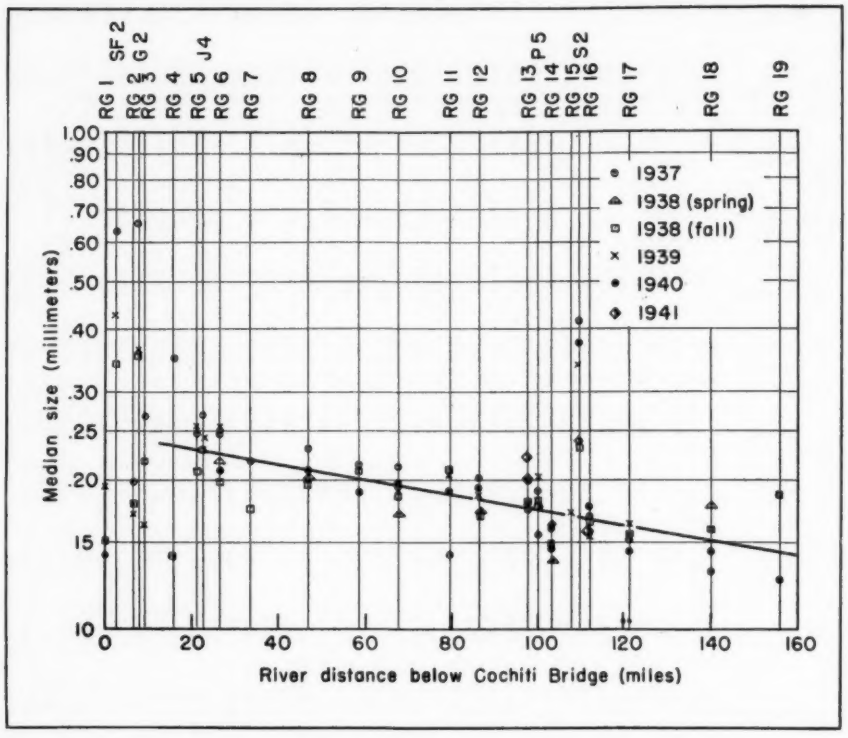

FIG. 7.—Median grain size of Rio Grande and tributary sands

amounts of biotite, muscovite, and other rarer micas, quartz, feldspars, and calcite (including other carbonates) occur in the heavy-mineral separates.

For the sand-source investigations certain varieties of some minerals were distinguished, and other minerals were grouped together. Thus, the hornblendes were divided into blue-green, green, and brown varieties on the basis of differences cause tremolite could not be differentiated rapidly and accurately from them. Several varieties of garnet, tourmaline, and zircon were present in most of the samples, but these varieties were not separately recorded. A small amount of other black, opaque minerals and some pyrite and pyrrhotite were included with ilmenite. Because they are not important in sand-source investigations, most of

the rarer minerals have been reported with the "unknowns."

Petrographic work for the Rio Grande investigation was done by five different men. This had introduced some personal bias into the results. It was recognized that such personal bias would occur; and, in so far as possible, the work was apportioned so that the contributions from particular tributaries or during particular years would be based on the work of only one person. Counts made as part of an experiment to determine the relative effectiveness of gravity and centrifuge separation[29] indicate that the results obtained by a single observer are comparable.

VARIATION IN MINERAL COMPOSITION

The number frequencies of heavy minerals vary both with size in a single sample and with difference in average size and degree of sorting in the same part of a stream.[30] Similarly, the weight of all heavy minerals varies with size in a single sample and with size and sorting in different samples. Even superficial examination of the Rio Grande and tributary number frequencies and weights showed that this is a characteristic of heavy minerals in stream deposits.

In the main stream and the tributaries certain differences in weight or frequency of heavy minerals are too large to be caused by these factors. These differences are so pronounced that the part of the drainage basin from which a sample has been derived may be ascertained by determining the weights of all heavy minerals or by superficial examination of the mineral suite. In the Rio Puerco, for example, the total weight of heavy minerals is relatively small, never exceeding 4 per cent of the sediment in any size grade, whereas in the Rio Salado and Santa Fe Creek the total weight is larger, often exceeding 10 or even 20 per cent in the 0.124–0.088-mm. size grade. Similarly, in the Rio Grande below San Acacia, New Mexico, brown hornblende is much more abundant than blue-green hornblende, whereas in the Rio Grande above Bernardo, New Mexico, the reverse is true. Some of these distinguishing criteria have been summarized in Table 10.

CONTRIBUTION FROM TRIBUTARIES TO THE MAIN STREAM BELOW THEIR JUNCTIONS

RIO SALADO

Heavy minerals indicate that, on the average, the Rio Salado contributes about 20 per cent of the sand transported past San Acacia by the Rio Grande (Table 11). Because the mineral composition of the Rio Salado differs greatly from that of the Rio Grande above its junction, this estimate is considered reliable.

Most useful are the minerals pyroxene, brown hornblende, and green hornblende, from which contribution was determined for three size grades for all four years, a total of thirty-six separate determinations. Ilmenite and apatite have also been used; but large "unexplained errors" of the former and the sampling error of the latter, particularly in the coarser size grades, make contribution as determined from them less reliable. The other minerals are present in such small proportions in one or more of the samples that the sampling error is very large. Although blue-green hornblende is in this group, it has been included in

[29] Rittenhouse and W. E. Bertholf, Jr., "Gravity versus Centrifuge Separation of Heavy Minerals from Sand," *Jour. Sed. Pet.*, Vol. XII (1942), pp. 85–89.

[30] Rittenhouse, ftn. 5 (1943).

Table 11, mainly to illustrate how great the error for this mineral is in the Rio Salado.

RIO PUERCO

In the Rio Puerco the relative frequency by number of the various heavy minerals does not differ greatly from that in the Rio Grande at Bernardo (RG 12). The total weight of heavy minerals in the Rio Puerco, however, is much lower than in the Rio Grande. Therefore, the hydraulic ratios in the Rio Puerco are smaller than in the Rio Grande, and the contribution from the Rio Puerco can be determined (Table 12). The difference in hydraulic ratios between the two streams, however, is much smaller than between the Rio Salado and the Rio Grande; and, consequently, errors of sampling are relatively more important. This is indicated by the greater variation in contribution from the Puerco, as shown in Table 12, and in the presence of more so-called "impossible cases," that is, cases where no mixture from the Puerco and the Rio Grande could produce the sand found below their junction.

With the exception of the 0.250–0.175-mm. size grade for 1941 and the 0.124–0.088-mm. size grade for 1938, however, the average contributions, as determined from the various minerals for the three size grades, vary within a relatively small range; and the major importance of the Rio Puerco as a contributor of sand to the Rio Grande is clearly indicated. It seems probable that the four-year averages of 65, 77, and 68 per cent for the three size grades examined are not greatly in error.

TABLE 10

MINERAL CHARACTERISTICS OF RIO GRANDE TRIBUTARIES

Tributary	Weight Percentage of all Heavy Minerals in the Fine Size Grades	Hornblende Content by Number in the Nonmagnetic Heavy Fraction of the Fine Size Grades	Relation of the Three Varieties of Hornblende	Magnetite in the Fine Size Grades (Percentage by Weight)
Rio Salado.....	High: 9–10 per cent	High: 20–30 per cent	Brown hornblende usually more abundant than green, and both very much more abundant than blue-green	1–2 per cent
Rio Puerco	Low: 2–3 per cent	Low: 5–8 per cent	Variable; brown and green hornblende usually about the same; blue-green usually less abundant than brown or green	Less than 0.5 per cent
Rio Jemez.....	Low: 2–4 per cent	Low: 5–8 per cent	Variable; all three varieties are about equally abundant	At J 2, more than 5 per cent
Rio Galisteo....	Intermediate: 3.5–8.0 per cent	High: more than 20 per cent	Blue-green hornblende usually more abundant than green, and green usually more abundant than brown	1–3 per cent
Santa Fe Creek..	High: 10–20 per cent	High: 20–40 per cent	60–85 per cent of the hornblende is blue-green; green usually more abundant than brown	Less than 1.5 per cent

RIO JEMEZ

The contribution of sand from the Rio Jemez (Table 13) is probably less accurate than that for either the Rio Puerco or the Rio Salado. The sands of the Rio Jemez carry a very small amount of

TABLE 11

CONTRIBUTION OF SAND FROM THE RIO SALADO TO THE RIO GRANDE AT SAN ACACIA, N.M. (RG 16)

MINERAL	SIZE GRADE											
	0.250–0.175 Mm.				0.175–0.124 Mm.				0.124–0.088 Mm.			
	1941 (Parts)	1940 (Parts)	1938 (Parts)	1937 (Parts)	1941 (Parts)	1940 (Parts)	1938 (Parts)	1937 (Parts)	1941 (Parts)	1940 (Parts)	1938 (Parts)	1937 (Parts)
Ilmenite*	0.69 ± 0.84		0.505 ± 0.202	0.050 ± 0.072	0.305 ± 0.171	0.013 ± 0.065	0.600 ± 0.216	0.035 ± 0.050				
Pyroxene	0.377 ± 0.133	0.156 ± 0.089	0.269 ± 0.068	0.087 ± 0.012	0.209 ± 0.090	0.066 ± 0.074	0.470 ± 0.166	0.129 ± 0.080	0.042 ± 0.033	0.480 ± 0.200	0.097 ± 0.064	0.167 ± 0.091
Blue-green hornblende	1.00 ± 1.37											
Green hornblende	0.153 ± 0.083	0.236 ± 0.179	0.234 ± 0.083	0.167 ± 0.086	0.110 ± 0.048	0.141 ± 0.044	0.92 ± 0.43	1.17 ± 5.83				
Brown hornblende	0.138 ± 0.062	0.407 ± 0.245	0.198 ± 0.060	0.337 ± 0.125	0.090 ± 0.032	0.232 ± 0.058	0.465 ± 0.138	0.243 ± 0.080	0.159 ± 0.044	0.600 ± 0.166	0.085 ± 0.040	0.338 ± 0.086
Apatite			0.81 ± 1.86			0.149 ± 0.410		0.105 ± 0.010	0.111 ± 0.032	0.348 ± 0.087	0.229 ± 0.081	0.170 ± 0.055
Weighted average (parts)	0.295	0.266	0.302	0.220	0.163	0.192	0.505	0.174	1.12 ± 1.83	0.21 ± 0.22	0.67 ± 0.67	0.60 ± 0.94
Weighted average (percentage)	23	21	23	18	14	16	36	15	12	31	18	21
Average of all years (percentage)	21				20				21			

* Ilmenite included with minerals one size grade larger because it is equivalent in hydraulic size to this coarser sand.

TABLE 12

CONTRIBUTION OF SAND FROM THE RIO PUERCO TO THE RIO GRANDE NEAR LA JOYA, N.M. (RG 14)

Mineral	Size Grade											
	0.250–0.175 Mm.				0.175–0.124 Mm.				0.124–0.088 Mm.			
	1941 (Parts)	1940 (Parts)	1938 (Parts)	1937 (Parts)	1941 (Parts)	1940 (Parts)	1938 (Parts)	1937 (Parts)	1941 (Parts)	1940 (Parts)	1938 (Parts)	1937 (Per Cent)
Ilmenite*	0.25±0.79	0.23±0.66	.....	.....	0.80±0.40	8.6± 11.3	.....	3.3± 3.3	.....	.....	.....	.....
Pyroxene	0.33±0.61	.....	.....	0.23±0.51	0.89±0.76	33.0±640	.....	.....	0.69±0.60	2.71±1.06	1.72±1.07	100.0
Blue-green hornblende	0.59±0.43	6.1 ± 5.5	2.66±1.03	.....	4.43±2.11	2.06±1.12	6.6 ±3.8	.....	1.53±0.61	1.27±0.46	1.71±1.01	100.0
Green hornblende	1.0 ±2.7	.....	.....	1.4 ±2.5	.....	0.25±0.71	1.62±1.58	6.7±12.4	.....	1.44±1.15	0.74±0.53	97.0
Brown hornblende	.....	4.5 ±13.0	.....	3.5 ±4.2	.....	.....	1.82±1.90	1.5± 5.9	.....	3.0 ±7.5	0.17±0.53	97.0
Apatite	.....	.....	0.82±1.44	.....	0.63±1.93	.....	.....	.....	.....	3.62±4.40	.....	.....
Hypersthene	.....	4.0 ±5.9	.....	.....	1.61±2.84	1.86±2.15	0.38±1.11	.....	2.66±1.90	0.80±1.23	2.22±2.58	.....
Weighted average (parts)	0.57	5.1	2.3	2.4	2.4	2.8	4.5	4.0	1.64	1.92	1.5	.....
Weighted average (percentage)	36	84	70	71	70	74	82	80	62	66	60	85†
Average of all years (percentage)	65				77				68			

* Ilmenite included with minerals one size grade larger because it is equivalent in hydraulic size to this coarser sand.

† Estimated.

TABLE 13

CONTRIBUTION OF SAND FROM THE RIO JEMEZ (J 4) TO THE RIO GRANDE AT BERNALILLO, N.M. (RG 6)

MINERAL	SIZE GRADE											
	0.250–0.175 Mm.				0.175–0.124 Mm.				0.124–0.088 Mm.			
	1940 (Parts)	1939 (Parts)	1938 (Parts)	1937 (Parts)	1940 (Parts)	1939 (Parts)	1938 (Parts)	1937 (Parts)	1940 (Parts)	1939 (Parts)	1938 (Parts)	1937 (Parts)
Pyroxene	.....	.....	0.90±1.19	.....	0.86±1.23	1.22±0.98	.....	7.4 ±14.1	0.55±0.57	.....	.....	0.91±1.08
Blue-green hornblende	0.37±0.28	0.51±0.30	0.24±0.28	0.87±0.37	1.32±0.43	0.11±0.19	0.39±0.28	1.36± 0.56	0.29±0.26	1.13±0.50	0.17±0.20	0.71±0.29
Green hornblende	.....	1.55±1.44	2.9 ±2.9	2.45±1.03	.....	0.29±0.48	0.37±0.58	0.08± 0.42	1.54±1.20	0.39±0.01	0.48±0.54	0.17±0.43
Brown hornblende	.....	.....	0.17±1.03	1.00±2.25	.....	2.7 ±9.0	0.36±0.98	1.8 ± 2.8	.....	.....	.....	0.60±0.74
Apatite	.....	0.50±1.52	0.40±0.81	.....	.....	1.3 ±2.0	1.0 ±3.0	15.0 ±66.0	.....	1.17±3.01	.....	.....
Weighted average (parts)	0.37	0.80	1.33	1.22	1.12	0.97	0.41	1.78	0.89	1.08	0.33	0.71
Weighted average (percentage)	27	44	57	55	52	49	29	63	47	52	25	42
Average of all years (percentage)	46				48				42			

heavy minerals other than magnetite and ilmenite, and the concentration of heavies in the Rio Grande above and below the Rio Jemez junction is not large. Consequently, the hydraulic ratios in the Jemez and Rio Grande are small, and sampling errors are relatively more important than in other places, where a greater difference exists between the hydraulic ratios in the tributary and main stream. These errors were reduced as much as time would permit by identifying more grains from each sample (an average of 684 each).

As for most of the other streams, pyroxene and the three varieties of hornblende have given the best data on relative contribution. The four-year averages of 46, 48, and 42 per cent for the three size grades investigated are considered to be of the right order of magnitude. This is confirmed by data obtained on the 1937 and 1938 samples earlier in the investigation. These data, though less accurate because of known errors in the heavy-mineral separations and because fewer grains were identified, indicated a contribution of 39 per cent from the Rio Jemez to the Rio Grande at Bernalillo.

RIO GALISTEO

The contribution of sand from the Rio Galisteo to the Rio Grande at San Felipe (RG 4), as presented in Table 14, appears to be reliable. The hydraulic ratios of pyroxene and the three varieties of hornblende in the Rio Galisteo are much larger than those in the main stream. Since the hydraulic ratios in the Rio Grande above and below the junction do not differ greatly, there is little doubt of the relative unimportance of the Galisteo as a source of Rio Grande sand.

Sampling locality RG 4 was used, instead of RG 3, as a base for the contribution determinations. The latter locality was so close to the junction that thorough mixing of the tributary and main-stream sands had not occurred. The mineral composition at RG 4 and RG 5 is very similar, but the hydraulic ratios there are much lower than at RG 3, where a concentration of Rio Galisteo sediment apparently occurs.

SANTA FE CREEK

The contribution of sand from Santa Fe Creek to the Rio Grande below its junction is presented in Table 15. In spite of the large number of zero contributions in the table, the average contributions as given are considered very reliable. The total weight of heavy minerals in Santa Fe Creek is very high, and consequently the hydraulic ratios in this tributary are also very high. The ratios in the main stream at Cochiti (RG 1) are relatively low, and the fact that the ratios at RG 2 (below the Santa Fe Creek junction) are also so low that no contribution from Santa Fe Creek is indicated for some minerals is itself a confirmation of the relative unimportance of Santa Fe Creek as a source of the Rio Grande sand.

Rio San Jose.—An attempt was made to determine what part of the Rio Puerco sediment originates in the area drained by the Rio San Jose and what part from the Rio Puerco above the junction with the San Jose. When the hydraulic ratios had been determined and were compared, it was found that the mineral composition of the San Jose and upper Rio Puerco were so similar that the relative importance could not be established accurately. Although there are some differences in number frequency of the heavy minerals from these two parts of the Rio Puerco drainage area, the total amount of heavy minerals is so

small that the hydraulic ratios show little difference.

Upper Rio Jemez.—The upper Rio Jemez is similar to the upper Rio Puerco identification of a much larger number of grains, the contribution from both the upper Rio Puerco and the upper Rio Jemez could probably be determined.

TABLE 14

CONTRIBUTION OF SAND FROM THE RIO GALISTEO (G 2) TO THE RIO GRANDE AT SAN FILIPE, N. M. (RG 4)

Mineral	Size Grade					
	0.246–0.175 Mm.		0.175–0.124 Mm.		0.124–0.088 Mm.	
	1938 (Per Cent)	1937 (Per Cent)	1938 (Per Cent)	1937 (Per Cent)	1938 (Per Cent)	1937 (Per Cent)
Pyroxene	9	13	.....	28	11	12
Blue-green hornblende	4	0	14	2	31	.....
Green hornblende	31	.....	26	15	88	0
Brown hornblende	6	47	2	20	12	0
Average	16	20	11	16	18*	4

* Omitting data for green hornblende.

TABLE 15

CONTRIBUTION OF SAND FROM SANTA FE CREEK (SF 2) TO THE RIO GRANDE AT RG 2

Mineral	Size Grade					
	0.246–0.175 Mm.		0.175–0.124 Mm.		0.124–0.088 Mm.	
	1938 (Per Cent)	1937 (Per Cent)	1938 (Per Cent)	1937 (Per Cent)	1938 (Per Cent)	1937 (Per Cent)
Pyroxene	0	7	0	10	19	38
Blue-green hornblende	0	1	0	2	0	7
Green hornblende	0	0	0	7	6	6
Brown hornblende	0	.....	0	0	2	4
Average	4*	6	4*	5	6	6†

* Estimated.

† Omitting data for pyroxene.

drainage area in that the differences in mineral composition are not great enough to permit accurate determination of the relative contribution from the two main subareas. With careful technique and

CONTRIBUTION OF TRIBUTARIES TO AREAS OF DAMAGE

In the Middle Rio Grande there are two major areas where damage has occurred and will occur in the future,

namely, (1) between San Acacia (RG 16) and San Marcial (RG 19), where sedimentation in the channel and floodway is rapid and damage has been and will be excessive, and (2) between Bernalillo (RG 6) and Bernardo (RG 13), where channel and floodway sedimentation is slower and damage has been moderate in the past but may be excessive in the future if present sedimentation rates continue or increase. To the first of these areas all five major tributaries have been contributors. To the second area, however, the Rio Puerco and Rio Salado are important only as their sediment has an upstream or backwater effect. Consequently, the relative importance of the various subsource areas as contributors of sand to these two parts of the valley is not the same.

Source data have been obtained only for the five major tributaries that join the Rio Grande in the Middle Valley and, by difference, for the main stream above Cochiti, New Mexico. Using these data alone, the contributions to the two main areas of damage are as follows: to the Rio Grande below San Acacia, the Rio Salado contributes about 21 per cent; the Rio Puerco, 56 per cent; the Rio Jemez, 11 per cent; the Rio Galisteo, 1.5 per cent; Santa Fe Creek, 0.5 per cent; and the Upper Rio Grande, 10 per cent. To the Rio Grande between Bernalillo and Bernardo, New Mexico, the Rio Jemez contributes about 45 per cent; the Rio Galisteo, 8 per cent; Santa Fe Creek, 2 per cent; and the Upper Rio Grande, 45 per cent. These percentages were obtained by computing separately the contribution from each stream for each of the three size grades examined and then averaging the results.

But small tributaries, for which no contribution data were obtained, drain about 17 per cent of the Rio Grande watershed. Although consideration of these small tributaries complicates the evaluation of sediment sources, they cannot be neglected. For source evaluations they may be grouped as follows: (1) those that enter the Middle Valley below the Rio Salado, (2) those between the junctions of the Rio Puerco and Rio Salado, (3) those between the junctions of the Rio Jemez and the Rio Puerco, (4) those between the junctions of the Rio Galisteo and the Rio Jemez, and (5) those between the junctions of the Rio Galisteo and Santa Fe Creek. The side drainage between Cochiti, New Mexico (RG 1), and Santa Fe Creek is negligible.

Sufficient data of other types were not available to estimate the quantitative importance of these minor tributary areas as sources of sand. It seemed probable, however, that the contribution of sand from these minor tributary areas would not exceed twice the average rate from the entire drainage area above San Marcial or would not be less than half the average rate. Some tributaries in each group might well exceed the upper limit, but high rates from these would tend to be offset by low rates from others which deposit much of their sand in alluvial fans along the edges of the main valley.

It has been assumed, therefore, that the sediment contribution to the Middle Valley deposits from each of the five minor tributary areas listed above is not more than twice and not less than half the average for the entire drainage area. Based on this assumption, the relative contributions of sand from the six major parts of the watershed and from the minor tributary areas as a group were computed and are presented in Table 16.

To compute the relative contributions in Table 16, it was necessary to know (1) the percentage contribution of each major tributary to the load of the Rio

Grande below the tributary junction, (2) the area of each of the five groups of minor tributaries for which source data were not obtained, and (3) the volumetric distribution of sediment in different sections of the Middle Valley. The percentage contributions used are those in Tables 11, 12, 13, 14, and 15. The areas of the five groups of minor tributaries are those presented on page 157.

Field surveys by Happ[31] show that the average annual accumulation of sediment in the Middle Valley during the period 1936–41 was 12,069 acre-feet. Of this total, 9,598 acre-feet were deposited between the Elephant Butte Reservoir and the mouth of the Rio Salado; 2,300 acre-feet between the Rio Jemez and the Rio Puerco; 385 acre-feet between the Rio Galisteo and the Rio Jemez; 72 acre-feet between Santa Fe Creek and the Rio Galisteo; and 70 acre-feet between Cochiti, New Mexico, and Santa Fe Creek. Between the Rio Puerco and Rio Salado there was a net scour of 356 acre-feet annually. These volumes are for sediment of all textures. Mechanical analyses of the deposits in different parts of the valley indicate that sand, of the sizes to which the mineral data are applicable, is present in about the same proportion in different parts of the valley. For convenience in computing the relative contributions presented in Table 16, the volumes of all sediment, rather than volumes of sand only, were used. The assumed range of sediment contribution from the minor tributaries thus was from 0.25 to 1.00 acre-feet per year per square mile of drainage area.

In making the computations all sediment from the direct drainage below the Rio Salado and between the Rio Puerco and Rio Salado was assumed to have been deposited below the Rio Salado. The sediment from the direct drainage between the Rio Jemez and Rio Puerco was assumed to have accumulated in the upper and lower areas of damage in the same proportion that the deposits between the Rio Jemez and Rio Puerco bear to the deposits below the Salado that came from above the Rio Puerco. Similar assumptions were made regarding the distribution of sediment from the other two areas, except that the sediment from the Jemez-Galisteo area was distributed to three sections of the valley and the sediment from the Galisteo–Santa Fe Creek area was distributed to four sections of the valley.[32]

TABLE 16

SOURCES OF MIDDLE RIO GRANDE SAND

Tributary Areas	To the Rio Grande between San Acacia and San Marcial, N.M.	To the Rio Grande between Bernalillo and Bernardo, N.M.
Rio Salado	18.8–20.5*	.....
Rio Puerco	48.4–54.1	.....
Rio Jemez	4.2– 8.7	21.2–39.4*
Rio Galisteo	0.4– 1.4	2.3– 6.3
Santa Fe Creek	0.1– 0.4	0.6– 1.9
Rio Grande above Cochiti	2.2– 8.1	11.1–36.6
Direct drainage	25.9– 6.8	64.8–15.8

* The range in contribution is based on the assumption that areas for which no data were available contributed sediment at from one-half to twice the average rate from the entire drainage area above San Marcial, N.M.

For the area of damage between San Acacia and San Marcial, a rather wide range in minor tributary contribution may occur without greatly changing the

[31] Happ, ftn. 2.

[32] Happ has obtained slightly different figures for the relative importance of the various sediment sources. He has assumed an annual rate of 0.5 acre-foot per square mile of drainage area and then introduced the total volume of sediment from all minor tributaries in a single step. He has also evaluated sources of all deposits in the Middle Valley rather than of deposits in specific areas of damage. Although Happ's single-step evaluation of

relative importance of the major tributaries. This is true because only a small part of the minor tributary drainage enters the Middle Valley below the Rio Puerco and because the Rio Salado and Rio Puerco contribute such a large proportion of the sand. Even if the minor tributaries deliver sediment at the maximum assumed rate, the Rio Salado and Rio Puerco deliver about two-thirds of the sand to this area. If the minor tributary rate were five times the average for the entire drainage basin above San Marcial ($2\frac{1}{2}$ times the maximum assumed rate), the Rio Salado and Rio Puerco together would still contribute more than half of the sand. In consequence, the contribution from all other parts of the watershed must be of secondary importance.

Although the Rio Puerco contributes several times as much sand to the Rio Grande between San Acacia and San Marcial as does the Rio Salado, the latter stream delivers more sand per unit of drainage area. The Rio Puerco drains about 21 per cent of the entire watershed area and contributes about half the sand; the Rio Salado drains about 6 per cent of the area and contributes about one-fifth of the sand. On a unit of drainage area basis the Rio Puerco contributes at a rate about $2\frac{1}{2}$ times that of the entire drainage basin above San Marcial; the Rio Salado at a rate about $3\frac{1}{3}$ times that of the entire drainage area. Actually, much of the sand from both these streams is derived from the lengthening and widening of arroyos, and for this reason the per unit of drainage-area rates are somewhat misleading. There is no question, however, that the two streams are very important sources of injurious sediment or that high priority must be given to them in considering measures for reducing or alleviating sediment damage in the lower Middle Valley. Of the other parts of the watershed the Rio Jemez appears to contribute at the highest rate, and the relatively large area above Cochiti appears to contribute at the lowest rate.

For the area of damage between Bernalillo and Bernardo the rate of minor-tributary contribution is much more important, and consequently the source evaluations are less accurate than those for the San Acacia–San Marcial damage area. Lack of data on the contribution from the minor-tributary area between the Rio Jemez and the Rio Puerco causes the most uncertainty. This area comprises nearly 2,200 square miles, and consequently a relatively small difference in rate means a large difference in sediment volume. What evidence is available, however, indicates that the sand from many of the tributaries within this area is deposited in alluvial fans and does not reach the Rio Grande channel or floodway. Consequently, it is thought that the actual rate of contribution from this area is well below the assumed maximum. Additional factual data regarding sediment delivery from this area are urgently needed.

For this damage area, however, the Rio Jemez is of first importance on a per unit drainage-area basis, since it delivers sand at a rate more than $3\frac{1}{2}$ times that of the entire drainage basin above Bernardo. The large area above Cochiti is probably of least importance, since it contributes at a rate less than half that of the drainage basin above Bernardo.

minor tributary contribution simplifies the mechanics of computation, it indirectly assumes very high rates of contribution from some of the five minor tributary areas and very low or negative rates from others. Happ's figures also indicate that the Rio Salado and Rio Puerco are less important, and the Rio Galisteo, Santa Fe Creek, and the Rio Grande above Cochiti are more important, than do the figures in Table 16.

Data have been presented for three $\sqrt{2}$ size grades. These data actually apply to sizes of light minerals that are about 0.2–0.3 ϕ larger than the heavies. Strictly, therefore, the data are applicable to sand between 0.287 and 0.101 mm. in diameter. In the area below San Acacia, however, sand in this range constitutes about 71 per cent of all channel sediment; in the area between Albuquerque and Bernardo it constitutes about 64 per cent of the channel deposits.

Because there appears to be no significant difference in contribution for the three size grades examined, it seems likely that essentially the same percentage contribution would hold for other sizes studied—certainly without great modification for the $\sqrt{2}$ size grades immediately coarser and finer than those for which data have been presented. If these two size grades are included, the results in Table 16 are applicable to about 90 per cent of the channel deposits below San Acacia and about 86 per cent of the channel deposits between Bernalillo and Bernardo. Even if sand of other sizes was brought from the various source areas in vastly different proportions, the relative importance of the subsource areas, as indicated in Table 16, would not be altered materially.

Strictly, these percentages apply only to the upper 3 or 4 feet of the channel deposits from which the samples were collected. Although equipment was not available for making deep borings in the unconsolidated channel deposits, sand of about the same texture probably extends to much greater depths, particularly in the lower Middle Valley. Within the floodway below Bernalillo, test borings to a depth of as much as 15 feet usually show no marked change in texture with increasing depth. Similar test borings outside the floodway indicate that the flood-plain cover of fine-grained silt and clay is also underlain by former channel sands of about the same texture as those in the present channel. When excavations were made for the Middle Rio Grande Conservency District diversion weirs, gravels were found at depths of about 30 feet below the low-water channel at the Angostura dam (above the mouth of the Rio Jemez), at the Isleta dam, and at San Acacia.[33] These dams are all located in narrow parts of the valley. Near Albuquerque, where the valley is wider, the piers of the Barelas bridge are set in a bed of gravel at a depth of 60–65 feet. The inference from the wording in the National Resources Committee report is that the sediment overlying the gravel at the dams and the bridge was sand.

VARIATION IN TRIBUTARY CONTRIBUTION WITH TIME

In May, 1937, there was a large flood in the Rio Grande between San Acacia and San Marcial, the discharge at the San Marcial gauging station on May 29 being about 25,000 cubic feet per second.[34] For the fifty-five-day period between April 16 and June 9, 1937, the discharge at San Marcial was more than 5,000 c.f.s. At Bernardo during the same period the maximum discharge was about 12,500 c.f.s., and daily discharges of more than 5,000 c.f.s. were reported between April 13 and June 9. This was a typical spring flood in the Middle Rio Grande Valley, most of the water having been derived from melting snow in mountains above Cochiti.

[33] National Resources Committee, *Regional Planning*, Part VI: *Upper Rio Grande* (Washington: National Resources Committee, 1938), p. 217.

[34] N. C. Grover *et al.*, "Surface Water Supply of the United States, 1937. 8. Western Gulf of Mexico Basins," *U.S. Geol. Surv. Water-Supply Paper 828* (1939), pp. 99–107.

During 1938, 1939, and 1940 there were no large spring floods in the Middle Rio Grande, although local storms from July through September, chiefly on the intermediate and lower parts of the watershed, produced small to intermediate floods on the various tributaries that join the Rio Grande in the Middle Valley.

In the spring of 1941 there was another large meltwater flood that originated in the mountains above Cochiti. This flood was the largest since 1929, at which time much damage had been done near San Acacia. During the 1941 flood the levees were breeched at several points in the valley, and several bridges or their approaches were washed out. The maximum daily discharge was about 23,000 c.f.s.[35]

Collection of samples for heavy-mineral sand-source investigations were made in the summer following the 1937 flood flows, in 1938, 1939, and 1940 during periods of relatively low water, and in 1941 following the flood of that year. Consequently, if contributions of sand from tributaries to the main stream vary greatly in relation to major and minor floods in the main and tributary streams, a comparison of the contribution from the various tributaries might be expected to show some systematic variations from year to year.

The yearly contributions from the Rio Salado suggest an apparent decrease in contributions following large floods. For the years 1937 and 1941 the contributions average about 18 and 16 per cent, respectively; for 1938 and 1940 the contributions were 26 and 23 per cent, respectively. These differences could be due to sampling errors. For the Rio Puerco and Rio Jemez, sampling errors apparently are greater than any fluctuations caused by floods on the main stream. For the other tributaries the data are not conclusive.

A comparison of the texture of samples collected at different times does not show greater variations than would be expected from sampling errors. Progressive coarsening of the deposits in the main stream at San Marcial from 1937 to 1940 is due to partial and later complete plugging of the channel farther upstream. Year-to-year differences in texture in the several tributaries and in the main stream above Bernalillo are probably due mainly to difficulties of sampling sediment that contains a large proportion of gravel.

FLOOD-PLAIN CONTAMINATION

Erosion on the outside and deposition on the inside of stream bends is a normal process in most rivers. In consequence, there may be a constant interchange of sediment, the eroded material being added to the stream load, the deposited material being removed. Marked changes in the mineral composition of the sediment in transit may result from this process For example, in tributaries flowing to the Mississippi across wide areas of the Delta, R. Dana Russell and L. W. Hough[36] report marked changes in mineral composition within distances of 30–50 miles. The extent of such flood-plain contamination in the Middle Rio Grande Valley has been considered.

In any stream the extent of flood-plain contamination will depend primarily on two factors, namely, (1) the amount of sediment added by bank-cutting or channel scour in comparison with the amount

[35] U.S. Geological Survey, personal communication.

[36] "Mineral Composition of Sands from Mississippi River Tributaries" (abstr.), *Bull. Geol. Soc. Amer.*, Vol. XLIX (1938), p. 109.

of sediment in transit, and (2) the amount and kinds of heavy minerals in the eroded and transit sands. In the rapidly aggrading Middle Rio Grande Valley, field evidence does not indicate that bank erosion is a particularly important source of sediment. Most of the low-stage cutting merely re-works the modern sands that have been temporarily deposited in the wide, unvegetated high-water channel. At higher stages the importance of bank-cutting is more difficult to evaluate because the river channel is deepened, and older sediments that underlie the modern deposits may be eroded. This high-stage bank- and bottom-cutting may be most important following avulsive changes in position of the Rio Grande channel. Such avulsions have occurred frequently in modern time, the most recent having occurred a few miles above San Marcial in 1938. The field evidence alone is not conclusive regarding the importance of flood-plain contamination in the Middle Valley.

Fairly conclusive evidence of the minor importance of flood-plain contamination in the Middle Valley below San Acacia is given by the mineral composition of the present and old sands. In this section of the valley the mineral composition of the old sands that underlie the flood-plain deposits of vertical accretion differs greatly from that in the present channel. In the old sands the hydraulic ratios of brown hornblende, green hornblende, and pyroxene are much lower, and the ratio of blue-green hornblende much higher, than in the present channel sands (Fig. 8).[37]

If these old sands were being eroded in considerable amount, the hydraulic ratios of pyroxene, brown hornblende, and green hornblende in the present channel deposits should show a progressive decrease in the 30 miles or so of transport between San Acacia and San Antonio, and the hydraulic ratio of blue-green hornblende should increase. Actually, no such decrease or increase occurs, and it thus seems probable that no great volumes of the old sands are eroded. It is quite possible, however, that some previously deposited modern sediment is eroded, but no data are available to indicate the extent of such flood-plain contamination, if any.

The sediment contributed to the Rio Grande by the Rio Salado has high hydraulic ratios for pyroxene, brown hornblende, and green hornblende and a low ratio for blue-green hornblende. In the modern channel deposits the hydraulic ratios of these minerals are generally similar to those in the Rio Salado. In the premodern deposits they are very different. Therefore, the relative contribution of sand from the Rio Salado to the Rio Grande must have increased very greatly as a result of accelerated erosion. Because the two San Acacia old-sand samples were collected from a former channel of the Rio Grande that was abandoned when the Santa Fe Railway was constructed about 1880, it also follows that the great increases in Salado contribution began sometime after about 1880. This agrees with conclusions by Bryan[38] that the valley trenching, which has been the source of much of the sediment contributed to the Rio Grande, started in the late 1880's or early 1890's. Perhaps through study of sands deposited in channels that were abandoned later, more accurate information on the time of arroyo-cutting in the Rio Salado could be obtained.

[37] Rittenhouse, ftn. 4.

[38] Ftn. 8 (1928).

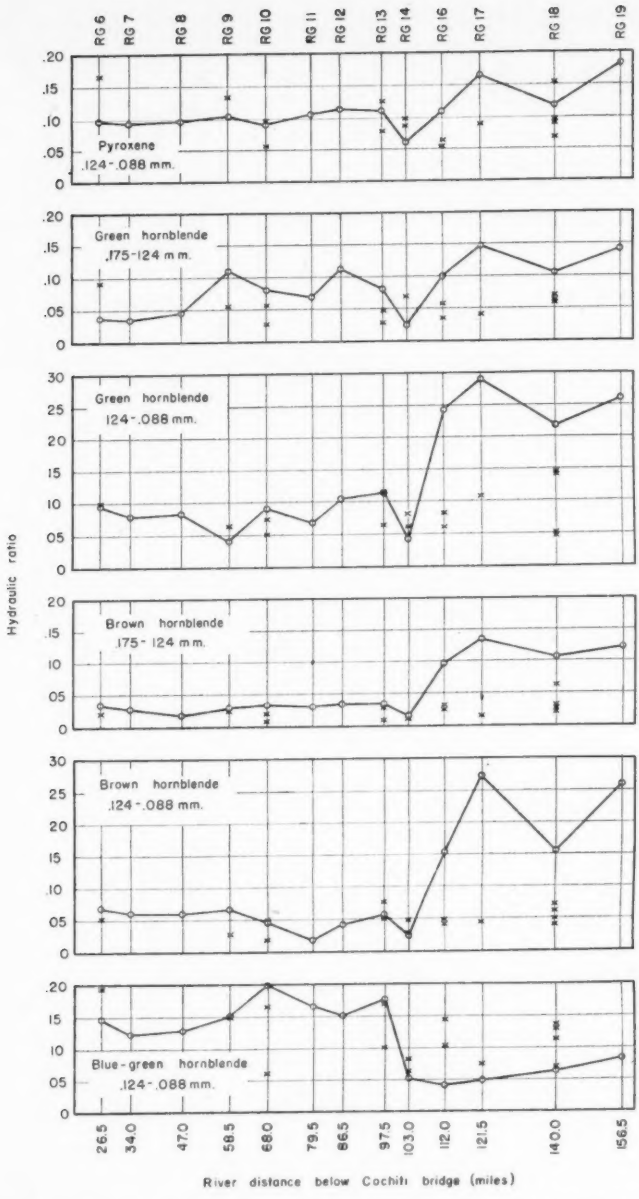

FIG. 8.—Hydraulic ratios of selected heavy minerals in modern channel sands (o) and old sands (×) in the Middle Rio Grande Valley.

In the section of the Middle Valley between Bernalillo and Bernardo the mineral evidence is less satisfactory. Here the mineral composition of the old sands has been determined from test-boring samples at Bernalillo (RG 6), Isleta (RG 9), Los Lunas (RG 10), and Bernardo (RG 13). With the exception of the Bernalillo sample, the hydraulic ratios in the old sands appear to change little with distance of transport (Fig. 8). The hydraulic ratios of the present channel deposits are of about the same order of magnitude. Consequently, even though flood-plain contamination was important in this section of the valley, the mineral composition of the present deposits would show little, if any, change between Bernalillo and Bernardo.

ACKNOWLEDGMENTS.—The help and co-operation of the many persons and organizations that have made this paper possible is gratefully acknowledged. The investigation was planned with, and carried out under, the general supervision of Dr. S. C. Happ, head of the Stream and Valley Section, Sedimentation Division, Soil Conservation Service. Dr. Happ's suggestions and comments were especially helpful. The aid of numerous field and laboratory assistants and the co-operation of the Universities of Chicago and North Carolina have already been noted (pp. 157 and 158). Helpful advice or aid was also given by G. C. Dobson, H. A. Einstein, C. B. Brown, E. M. Thorp, A. G. Anderson, R. G. Grassy, J. W. Johnson, Gene Zwerner, W. F. Witzgall, E. E. Mahon, and A. E. Brandt, of the Soil Conservation Service, and Dr. F. J. Pettijohn and Walter Bartky, of the University of Chicago. Calculating-machine operations were provided by the Works Progress Administration and the National Youth Administration.

HYPOTHESIS OF SUBGLACIAL EROSION

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ABSTRACT

Belief that ice at the base of thick glaciers is too plastic and likely to contain too much intergranular meltwater for effective plucking of underlying rock leads to the hypothesis that pressure-controlled freezing of small amounts of meltwater in joints immediately beneath the glacier has been a significant factor in the vast amount of subglacial block removal that has evidently occurred. Outward flow of glacier-derived ground water is believed adequate locally to remove geothermal heat which otherwise would prevent freezing below the floor level. The floor rock serves to store and to release heat as the pressure-melting-point shifts. Any freezing beneath a joint-bounded block tends to lift it and to permit ice and debris to wedge around and beneath it.

Roches moutonnées are a logical consequence of extensive operation of the process, and numerous recorded instances of other types are believed also to illustrate the principle.

INTRODUCTION

The manner in which deep glacial ice loosens and removes joint-bounded blocks of bedrock is in question. In plucking, as commonly described, the ice freezes firmly to the rock and pulls the blocks away as the glacier moves forward. But such a concept is quite out of keeping with the highly plastic nature of ice at the base of thick glaciers, as recently interpreted in two excellent papers by Max Demorest.[1] C. A. Cotton[2] has emphasized the difficulty of reconciling ice plasticity with plucking in discussing the origin and development of the characteristic "steps" along a glaciated valley, as well as in cirque-wall sapping. Unpublished work by the present writer indicates that some mode of block removal dominated glacial erosion in the plateau region of New York. The inference is that plastic ice beneath thick glaciers—both valley and continental types—does effect block removal by some process in which tensional stress is, or may be, a negligible factor.

The present paper seeks to explore the possibilities of bedrock disruption by pressure-controlled freezing of meltwater in joints beneath deep glacial ice. The hypothesis postulates an adequate supply of basal meltwater, some of which escapes by deep percolation along bedrock joints. Variations in pressure from weight of overlying ice may then suffice to promote effective freezing of water in the upper bedrock zone by shifting the pressure-melting-point so as to cause interchange of heat between rock and joint-held water and ice. Although interpretations must rest chiefly on indirect evidence, the importance of the problem justifies a search for adequate explanation.

Before the effects of reasonable variations in pressure can be evaluated, it is necessary to review the pressure-temperature relationship within thick glaciers, to evaluate the probable amounts of meltwater within and beneath the ice, and to note the probable groundwater conditions beneath the glacier.

[1] "Ice Flowage as Revealed by Glacial Striae," *Jour. Geol.*, Vol. XLVI (1938), pp. 700–725; "Glacier Thinning during Deglaciation, Part I: Glacier Regimens and Ice Movement within Glaciers," *Amer. Jour. Sci.*, Vol. CCXL (1942), pp. 29-66.

[2] "The Longitudinal Profiles of Glaciated Valleys," *Jour. Geol.*, Vol. XLIX (1941), pp. 113–28.

PRESSURE-TEMPERATURE EQUILIBRIUM

Except in the Antarctic region, seasonal variations of temperature within large glaciers seldom extend to depths greater than 10–15 meters. Below this surficial zone the temperature of pressure-melting prevails. Assuming that each additional atmosphere of pressure lowers the pressure-melting-point 0.0072° C.,[3] the decrease downward would be approximately 0.0192° C. through each 100 feet of ice. Once the temperature within a glacier becomes adjusted at the melting-point for the existing pressure, any increase in pressure liquefies some of the ice. As recently stated by W. V. Lewis,[4] the ice in melting

> .... will absorb its latent heat from the surrounding ice, the temperature of which will therefore fall. The process will continue until the temperature of the remaining ice has fallen to the melting point at the new pressure. By this means the deeper layers of the glacier will everywhere adjust their temperatures to the pressure-melting point, provided there is no further loss of heat for reasons not yet known.[5]

This principle is presumably applicable to glaciers of any thickness, and the pressure-temperature equilibrium is believed to be as delicately adjusted at the base of a glacier as it is near the surface or in the laboratory.

BASAL MELTWATER

Meltwater existing beneath or within a glacier must be in temperature equilibrium with the adjacent ice, and any excess heat which the water may have is promptly lost by additional melting. Frictional heat from movement, abrasion, and crushing of rock causes some melting, especially along the more rapidly flowing basal currents of the glacier; but surface melting and compression within the glacier may supply a greater amount either directly or indirectly. On Spitzbergen glaciers, where seasonal variation of temperature extends to a depth of 10 meters, H. W. Ahlmann[6] found that freezing of summer meltwater penetrating that zone soon brings the temperature to 0° C. Quantities of meltwater continue to sink into the firn and probably drain away ultimately along the base of the ice, though Ahlmann did not speculate as to its mode of descent. Downward migration of meltwater may occur along intergranular boundaries;[7] but the outflow of basal ice, as explained by Demorest,[8] would bring the water to lower levels regardless of any downward percolation. Because of lower pressure-melting-points at greater depths, the meltwater must transfer its excess heat by melting the requisite amount of ice as descent continues. Meltwater arriving at the base of a glacier 5,200 feet thick would have acquired a temperature of about −1° C., and its volume would have been augmented approximately 1/80 by melting additional ice en route. In similar fashion, the temperature of the névé must decline with increasing depth of burial until, beneath 5,200 feet of ice, the heat released will have melted about 1/80 of the original mass.

Compression of air entrapped in the

[3] James Dewar, "On the Lowering of the Freezing-Point of Water by Pressure," *Proc. Roy. Soc. London*, Vol. XXX (1879–1880), pp. 533–38.

[4] "The Function of Meltwater in Cirque Formation," *Geog. Rev.*, Vol. XXX (1940), pp. 64–83.

[5] *Ibid.*, p. 83.

[6] "Scientific Results of the Norwegian-Swedish Spitzbergen Expedition in 1934. Part I–VIII," *Geografiska Annaler 1935* (1936).

[7] O. D. von Engeln, "Experimental Studies and Observations on Ice Structure," *Amer. Jour. Sci.*, Vol. XL (1915), pp. 449–73.

[8] Ftn. 1 (1942).

névé is a further cause of melting within glaciers. As with the descent of surface meltwater, the heat of compression is released gradually as snow accumulation and outflow of basal ice bring the occluded air to lower levels. Beneath 5,000 feet of ice the pressure is approximately 132 atmospheres. Evidence of final escape of such air is suggested by J Harlen Bretz's description[9] of iceberg phenomena along the East Greenland coast.

"Millions of tiny bubbles of compressed air . . . . are released by melting . . . . " and, in rising along the sides of the icebergs, they generate upward currents of water that develop conspicuous fluting of the ice surface. After an iceberg breaks up, " . . . . for hours . . . . the fiord crackles like a fire in heavy dry grass as millions of compressed air bubbles continue to burst in the newly fractured surfaces of the comminuted ice."[10]

Certain ice-abrasion phenomena, particularly the intricate, curving striae and polished fluting on the bedrock of Kelly's Island led T. C. Chamberlin[11] to conclude that "the mobility of glaciers is facilitated by saturation with water." Similarly, a highly plastic or fluid-like medium must have produced the unusually high polish on many stones from some clayey tills, developed equally on sharply concave surfaces and on convex surfaces. The phenomenon is well illustrated in some of the north-sloping valleys along the northern margin of the Allegheny Plateau in New York. Interpretation of observed effects, therefore, as well as inference from applicable principles, favors the probability that the basal ice of a glacier contains much meltwater in temperature equilibrium with the ice. Such water would fill the joints in the glacier floor and would supply an outward flow of ground water from the glacier-covered area. The temperature of the water as it enters the joints would be that of the ice at the glacier floor, which varies slightly with pressure.

Outflow of ground water from beneath an extensive glacier would take place according to principles explained by F. H. King.[12] Assuming an abundant supply of meltwater, that which enters the bedrock at a distance back from the glacier margin must flow downward and outward beneath water originating nearer the point of escape. Actual lines of flow are governed by factors of permeability, but water entering the bedrock a few tens of miles back from the margin of a Pleistocene continental glacier may well have caused active circulation through the deepest joints. In favorable areas the downward-percolating water could have removed all the heat being conducted from the earth's interior, leaving the rock near the glacier floor at essentially the same temperature as that of the basal ice. Beneath 5,000 feet of ice, the temperature of maximum water density is about 0.75° C.,[13] or 1.75° C. above the temperature of pressure-melting at that depth. Therefore, the initial warming of meltwater brings increased density and prevents any upward transfer of heat by convection. At least locally, joints in the glacier floor could be filled with water at the pressure-melting temperature.

[9] "Physiographic Studies in East Greenland," in *The Fiord Region of East Greenland*, by Louise A. Boyd ("Amer. Geog. Soc., Spec. Pub.," No. 18 [1935]), pp. 159–266.

[10] *Ibid.*, p. 244.

[11] "The Rock Scorings of the Great Ice Invasions," *U.S. Geol. Surv., Ann. Rept. 7* (1886), pp. 147–248. Ref. p. 174.

[12] "Principles and Conditions of the Movements of Ground Water," *U.S. Geol. Surv., 19th Ann. Rept.*, Part II (1899), pp. 59–294.

[13] H. T. Barnes, *Ice Formation* (New York: John Wiley & Sons, 1906), p. 46.

PRESSURE VARIATION BENEATH GLACIERS

Variation in ice thickness and in quantity of load carried causes corresponding variations in pressure upon the glacier floor and therefore brings corresponding changes in the pressure-melting-point. During winter the outflow of ice from a cirque is greatly reduced, and snow accumulation is at a maximum, lowering the pressure-melting-point. In late spring renewed outflow reverses the trend. In some Swiss glaciers the spring outflow begins with relative suddenness and may produce a series of névé waves that progress slowly downvalley.[14] At the height of glaciation the annual variation of ice thickness in many cirques may have been as much as 35 feet.[15] The annual precipitation on the Vatnajökull in Iceland is approximately 256 inches, though part falls as rain.[16] Drifting by wind is an important factor in actual snow accumulation, especially in mountainous terrain, and probably was also in the marginal zones of the Pleistocene ice sheets. Differences in ice thickness from summer to winter in the more active portions of the continental glaciers may have been as much as 35 feet in some places.

Variations in pressure beneath parts of continental glaciers may arise also from intermittent movement of marginal lobes or segments. Interpreting from experiments by von Engeln,[17] renewed movement in a minor glacial lobe, following an interval of stagnation, requires a greater pressure gradient than that which is necessary for continued flow after movement has begun. Thus, intermittent movement would provide for increase and decrease in pressure upon the glacier floor, though the frequency and magnitude of variation are problematical.

Concentration of glacier flow in bedrock channels beneath the marginal zone of an ice sheet should afford greater-than-average variations in pressure. Evidence of such flow in eastern Greenland is well stated by Bretz,[18] who also summarizes earlier observations regarding the "basins of exudation" that are believed to mark the landward ends of fiord valleys. Comparable conditions must have obtained in the Allegheny Plateau of New York while the "through" valleys were being formed. Any decrease in rate of movement, perhaps because of increased load, would permit partial filling of the depression in the glacier surface, thereby increasing the pressure, while acceleration of flow would lead to decreased pressure.

Times of rapid reduction of pressure because of excessive melting should have accompanied the waning stages of Pleistocene glaciation in the middle latitudes, especially where increased summer melting was the chief mode of deglaciation. Ahlmann[19] found that surface melting on the Spitzbergen glaciers goes on 32 per cent faster after the snow cover disappears and the ice itself is exposed. Seasonal increase and decrease of pressure upon the glacier floor would then be superposed upon the general decline, with especially marked decrease in summer.

[14] R. Streiff-Becker, "Glacialerosion und Eisbewegung," *Vierteljahrschrift der Naturf. Gesellsch. Zurich*, Jahrg. 79, Hefte 1–3 (1934), pp. 195–208.

[15] Demorest, personal communication, 1941.

[16] H. W. Ahlmann and S. Thorarinsson, "The Vatnajökull Glacier: A Preliminary Report on the Work of the Swedish-Icelandic Investigations 1936–1937," *Geog. Rev.*, Vol. XXVIII (1938), pp. 412–38.

[17] P. 471 of ftn. 7 (1915).

[18] P. 239 of ftn. 9 (1935).

[19] Ftn. 6 (1936).

Transportation of the glacial load involves local changes in pressure, some of which are probably great, although they may be of short duration. Chattermarks and crescentic gouges may record such accumulation and relief of stress.

EFFECTS OF PRESSURE VARIATION

The consequences of shift in melting-point because of variation in pressure may be reviewed by considering first the conditions of early spring when pressure upon the cirque floor is at a maximum and ice temperature therefore at a minimum. Water from the basal ice has been moving into the floor joints, and a considerable thickness of rock has acquired essentially the temperature of the ice and percolating water. Then outflow and surface melting reduce the pressure, and the pressure-melting-point rises in response. When ice thickness has decreased 35 feet, the melting-point will have risen approximately 0.007° C. This is equivalent to 0.007 calories per cubic centimeter of water; and, because extraction of about 80 calories of heat would be required to freeze a cubic centimeter of water, the amount of ice resulting directly from this freezing-point shift is negligible. However, the adjacent rock also must be warmed to the higher pressure-melting-point temperature, and this absorption of heat will freeze a thin film of ice on the rock surface.

In middle latitudes during the Pleistocene, the period of decreasing pressure may have lasted 5 months of the year, during which time the rock could absorb much heat in spite of its relatively low coefficient of heat conductivity (assumed to average 0.008). But the heat capacity of the rock imposes a limit on the amount of heat that can be absorbed to form the ice. Recorded values for heat conductivity and for specific heat vary widely.[20] But assuming 0.2 gm. cal. as the specific heat, and a pressure-melting-point rise of 0.007° C., the heat capacity of rock 1 meter thick would suffice to freeze a small fraction of a millimeter of ice. Water held in a joint loses heat to both rock surfaces, and under favorable circumstances complete freezing could occur. Heat absorption would expand the rock slightly, thus tending also to strain the rock.

When next winter's snowfall brought increasing pressure, the rock would begin to give up its heat, and the first melting would loosen the ice from the rock surface. The slight expansion of the joint gained by the freezing, and the lubricating effect of the water film against the rock, would permit the ice to penetrate deeper into the crevice and would promote entrance of overlying ice and fine debris. The ice would penetrate a little deeper with each succeeding season of repeated freezing and melting, though the new ice pressure against the joint walls could never exceed the reduction in pressure from decreased weight of ice.

Outflow of ground water would in itself tend to promote penetration of glacier ice into the passageways, whose minimum width might be only a fraction of a millimeter, though no effective wedging could occur without additional freezing. A most significant feature of the hypothetical process here outlined is that it can act vertically as well as horizontally and tends to lift, rather than to pull, joint-bounded blocks, as in cirque-wall sapping or in excavation from a cirque floor. Extensive rock fracturing in a single season is not necessary in order to account for the observed results of block

[20] F. Birch *et al.*, *Handbook of Physical Constants* ("Geol. Soc. Amer., Special Papers No. 36" [1942]). Pp. 325.

removal. Assuming that Pleistocene ice activity lasted 400,000 years in mountainous regions in middle latitudes, a cirque 2,000 feet deep would require an average rate of deepening of only 1 foot in 200 years.

Where an impervious glacier floor prevented the entrance of meltwater, and where no deeper ground-water flow of glacial origin was taking place, geothermal heat would be conducted to the base of the ice, and no freezing would occur below the floor level.

APPLICATION OF THE HYPOTHESIS

The foregoing hypothesis suggests that no sharp boundary separates the moving ice from its nonmoving floor in areas where block removal and ready outflow of ground water are in progress, because blocks in all stages of loosening and removal grade downward into undisturbed bedrock. Deepest penetration of glacial ice would occur where joint widening was easiest, and the relative depth attained would vary from place to place; but the process would be delicately responsive to structural differences in the rock. Transportation of the loosened blocks could continue during the late declining stages of glaciation, when further loosening would be greatly reduced. Bedrock masses projecting above the excavated sites would remain as the characteristic *roches moutonnées*. In shaping them, pressure-controlled freezing of water films in joints might aid materially in removing blocks from the lee side, although the chief process here might well be shoving and plucking, as described by F. Matthes.[21] However, plucking by tension at any place where reduced pressure tends to cause the ice to freeze to the rock cannot be very effective unless the ice is relatively free from intergranular meltwater. Any considerable excess of the latter would leave the ice too plastic or nonrigid for effective tensional stress, and perhaps also for effective shoving. Nevertheless, the implication that continued removal of blocks from the lee sides of *roches moutonnées* would ultimately destroy them emphasizes the necessity for some process of bedrock excavation that will renew or replace the forms if they are to be regarded as characteristic of extensive glacial erosion.[22]

Progressive enlargement of joint crevices through which meltwater is escaping by ground-water flow may explain the occurrence of such phenomena as the clastic dike of glacial origin near Keene, New Hampshire, described by F. C. Kruger.[23] The mass is a "diagonal and horizontal branching dike" with maximum thickness of 5 inches. No size-sorting is evident. Basal ice penetrating a bedrock joint would carry with it any accompanying debris small enough to enter the fissure. Then, should deglaciation intervene before the adjacent loosened block or mass of rock could be removed, the debris would remain as a clastic dike.

In 1843 James Hall[24] described a more extensive occurrence of drift intruded into previously undisturbed bedrock along the Lake Erie shore in southwestern New York. Strata of about 10 feet maximum thickness[25] and a quarter

[21] "Geologic History of Yosemite Valley," *U.S. Geol. Surv., Prof. Paper 160* (1930). Pp. 137.

[22] Von Engeln, "Glacial Geomorphology and Glacier Motion," *Amer. Jour. Sci.*, Vol. XXXV (1938), pp. 426–40; Demorest, "Glacial Movement and Erosion: A criticism," *Amer. Jour. Sci.*, Vol. CCXXXVII (1939), pp. 594–605.

[23] "A Clastic Dike of Glacial Origin," *Amer. Jour. Sci.*, Vol. XXXV (1938), pp. 305–7.

[24] *Natural History of New York: Geology of the Fourth District* (Albany: C. van Benthuysen, 1843). Pp. 683.

[25] *Ibid.*, Pl. 8.

of a mile in extent had been lifted and moved forward almost as a unit, but with some local shattering. Drift had entered beneath the mass in places sufficient to striate the separated bedding surfaces. "In this instance, it only requires that a longer continued operation should have broken up the whole of these uplifted strata, to have left a tolerably even surface, scored and striated like all other strata surfaces described."[26] Disturbance of this type can be explained only as a result of lifting before, and during, forward movement. The relatively thin rock sheet could not have transmitted the necessary lateral thrust from ice-shove. R. D. Salisbury[27] and F. T. Thwaites[28] have described comparable occurrences.

ACKNOWLEDGMENTS.—While assuming all responsibility in presenting the foregoing hypothesis, the writer is pleased to acknowledge helpful discussions and criticism from the late Lieutenant Max Demorest and from Major Richard Foster Flint.

[26] *Ibid.*, p. 328.

[27] "On the Drift or Pleistocene Formations of New Jersey," *Geol. Surv. New Jersey Ann. Rept. 1891* (1892), pp. 35–108.

[28] "A Glacial Gravel Seam in Limestone at Ripon, Wisconsin," *Jour. Geol.*, Vol. XXIX (1921), pp. 57–65.

STUDIES FOR STUDENTS

THE STEREOGRAPHIC PROJECTION, A HANDY TOOL FOR THE PRACTICAL GEOLOGIST

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INTRODUCTION

One of the chief skills which the worker in structural geology must develop is facility in three-dimensional thinking and in ready visualization and computation of the angular relations between lines and planes in space. No other single, simple tool is so useful to that end as the stereographic projection.

In 1920 the writer called attention to its value in the study of joints.[1] In 1924, O. Seitz[2] pointed out its wide applicability, and later Rudolph Sokol[3] included a number of examples in his *Geologisches Praktikum*. More recently, Masanobu Morishita[4] made use of it in print in connection with fault problems. In America, D. Jerome Fisher[5] has set forth the ease with which problems of space relations may be treated with its aid. But still no American textbook of structural geology mentions the stereographic projection as a tool; and the writer's contact with colleagues and students confirms his impression that, on the whole, it is little used by geologists. It seems that there is

[1] Walter H. Bucher, "The Mechanical Interpretation of Joints," *Jour. Geol.*, Vol. XXVIII (1920), pp. 716–18.

[2] "Das Wulff'sche Netz als Hilfsmittel bei tektonischen Untersuchungen," *Berg- und Hüttenmännische Zeitschr. "Glückauf,"* Jahrg. 1924, No. 19.

[3] *Geologisches Praktikum* (Berlin, 1927).

[4] "On the Graphic Method of Representing Faults and Strata," *Jap. Jour. Geol. and Geog.*, Vol. XIV (1937), pp. 207–39.

[5] "Problem of Two Tilts and the Stereographic Projection," *Bull. Amer. Assoc. Pet. Geol.*, Vol. XXII (1938), pp. 1261–71.

Fisher has devised a special protractor which gives the radii of the great and small circles for a stereographic net of radius 5 cm. and scales for use with the stereographic and gnomonic projections. With its aid, the elements of any problem in spherical trigonometry may be constructed readily (on blank paper or, better, on Penfield paper, bearing a graduated circle). If the constructions are carried out with precision, results may be secured accurate up to a quarter of a degree. In structural geology, such accuracy is, however, of little or no value in all but exceptional cases. Bore holes are never straight; they often deviate widely from the intended course; bedding and fracture planes are practically never planes in the geometric sense, varying by degrees rather than by minutes in short distances; and the average rock surface is so uneven that readings accurate within 1° may be considered good. Three-dimensional visual representation of all the elements involved in a problem and utmost simplicity of construction may, therefore, safely be given preference to greater accuracy and mathematical elegance. This paper is, accordingly, limited entirely to the graphic use of the simple (meridional) stereographic net.

Where greater accuracy is needed, as in crystallography, astronomy, mathematical geography, and navigation (especially "avigation") Fisher's method is invaluable. Some of its applications are given in the following of his papers: "A New Projection Protractor," *Jour. Geol.*, Vol. XLIX (1941), pp. 292–323 and 420–44; "Drill Hole Problems in the Stereographic Projection," *Econ. Geol.*, Vol. XXXVI (1941), pp. 551–60; "Measuring Linear Structures in Steep-dipping Surfaces," *Amer. Min.*, Vol. XXVIII (1943), pp. 204–8; "Making Crystal Models," *Amer. Min.*, Vol. XXVI (1941), pp. 718–26. (The method described can be used for models of mines and certain geological structures.) For references to practical applications of the stereographic projection to problems in these fields see the first of Fisher's papers.

a tendency to regard it rather as something favored by individuals with a flair for mathematical toys and unsuited to the hard-hitting practical man. In order to show once again that the exact opposite is true, the following examples are put down in print as an encouragement to others to get in the habit of using this simple, straightforward, and effective tool.

The problems which constitute this paper were set down originally by the writer for the use of his students. He has been urged to make them more widely available and has reluctantly consented to submit them for publication. The chief value of a paper like this lies in simplicity in presentation, which is needed to help the practical geologist to overcome a natural distrust of "fancy" methods. To that end the projection is used pictorially throughout, and successive major steps in the solution of the problems are illustrated by successive drawings[6] instead of by placing all lines into one diagram, as one would do, of course, in actual practice.

The problems that are discussed in this paper cover the following subjects:

Problems not involving rotation:

Problem 1. Find the apparent dip in a vertical plane cutting an inclined bed.

Problem 2. Find the position in space of the line of intersection of two inclined planes—for example, a bed and a dike.

Problem 3. Find the angle between two conjugate shear planes and the attitude in space of its bisectrix, that is, the direction of maximum relative shortening of the strain-ellipsoid.

Problem 4. Find the position in space of striations of given pitch on an inclined plane of given dip and strike.

Problem 5. Find the angle which slaty cleavage forms with the axis of an inclined drill core when the position in space of the bore hole and the plane of cleavage are given.

[6] The writer wishes to thank the students in his graduate class in structural geology for help in preparing the illustrations used in this paper.

Problem 6. Find the length and position in space of the net slip on an inclined fault that cuts an inclined bed when the positions in space of the fault and the bed and the trend of the slickenside striations are given.

Problem 7. Find the length and position in space of the net slip on an inclined fault that cuts two beds of different inclination when the attitudes in space of the fault and the beds are given.

Problems involving rotation:

Problem 8. Find the attitude in space of a bed that is cut by two vertical bore holes when the location of the points of intersection in the bore holes and the angle between the bed and the axis of the drill core are given.

Problem 9. Same as Problem 8 but with the second bore hole slanting.

Problem 10. Find the point at which an inclined bore hole will intersect an inclined vein when the location and attitude in space of bore hole and vein are given.

Problem 11. Find the original attitude in space of inclined beds lying beneath a differently inclined unconformity and overlying beds when the attitude in space of both series of beds is given.

Problem 12. Find the dip and strike of beds on the displaced side of an inclined rotational fault that cuts horizontal beds when the attitude in space of the fault and the angle of rotation are given.

Problem 13. Find the angle of rotation on an inclined rotational fault when the attitude in space of the fault and of the beds on both sides of the fault are given.

Problem 14. Find the attitude in space and the location of the shortest distance between two drifts inclined at different angles in different directions that run past each other in a mine.[7]

THE STEREOGRAPHIC PROJECTION

Figure 1*a* shows the essential nature of the stereographic projection as applied to problems in structural geology. It shows the lower half of a sphere with the equatorial plane placed in a horizontal position. The stereographic projection is

[7] See also Walter H. Bucher, "Dip and Strike from Three Not Parallel Drill Cores Lacking Key Beds (Stereographic Method)," *Econ. Geol.*, Vol. XXXVIII (1943), pp. 648–57.

produced by drawing straight lines from the upper pole P through the points on the lower hemisphere and extending them to their intersections with a horizontal plane at any desired distance below the hemisphere.

In the resulting projection, every point represents a corresponding point on the hemisphere. In Figure 1*a*, for instance, the point C' represents the point C which lies in the right front quadrant of the hemisphere. The point O' may be said to represent two points: the center O of the horizontal equatorial plane, from which the radii of the hemisphere extend downward in all directions, and the lowest point of the hemisphere which lies vertically below O.

Correspondingly, a line which connects the point O' with any other point in the projection is the picture of a line in space. The line $O'C'$, for instance, is the picture of the line OC, which bears S. 60° E. and plunges 30°.

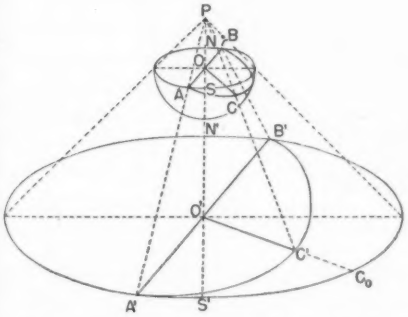

FIG. 1*a*.—Diagram showing an inclined plane ACB on the reference hemisphere and its stereographic projection ($A'C'B'$) onto a horizontal plane.

By providing the hemisphere with suitably drawn meridians and parallels and projecting them, a "stereographic net" is produced which allows the angles of trend and plunge of every line to be read in the same manner in which spherical angles are read on a map. In the following pages, this stereographic net will be referred to as "stereonet."

For the purposes of the geologist the most suitable arrangement of the coordinates is that reproduced in Figure 1*c*. This is known as a meridian stereonet,[8]

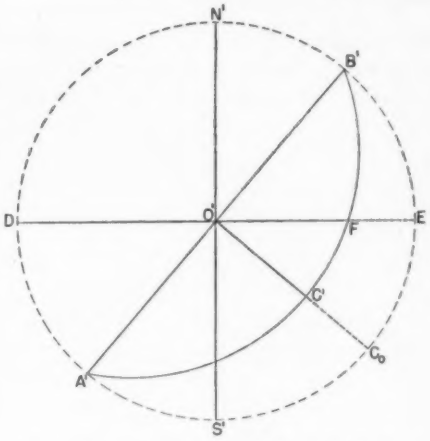

FIG. 1*b*.—Stereogram ($A'C'B'$) of the inclined plane ACB and the line of intersection with the vertical plane $O'E$. The line $O'F$, which lies in the plane, plunges EF degrees and bears $N'E$ degrees east of north.

since the circles on it may be considered as projected stereographically onto the plane of a meridian of the globe. The geologist places a piece of transparent paper above this net; and on this he pre-

[8] Copies of the stereonet identical with Fig. 1*c* may be obtained from the University of Chicago Bookstore. These are printed on heavy white poster board; price, seven nets for 25 cents postpaid. This shop also sells, for the same price, 25 sheets of stabilized tracing paper cut to field notebook size and imprinted with the Penfield protractor circle (cf. Figs. 15–17) to fit the stereonet. It is very convenient to use the poster-board stereonet with a sharpened thumbtack stuck through it from the rear. Before placing the protractor-circle paper on this, draw north-south and east-west diameters to locate the center.

Meridian stereonets to 2° intervals and of diameters 7.5 and 4.5 inches on plain paper may be secured from the Columbia Geographical Press, Co-

pares a stereographic projection, called a "stereogram." This is generally *not* made on a meridian plane but is often on one at right angles to this (cf. Fig. 1*a*). In visualizing the following problems it is very important to remember this point; that is, that the stereonet serves simply as a convenient sort of scale.

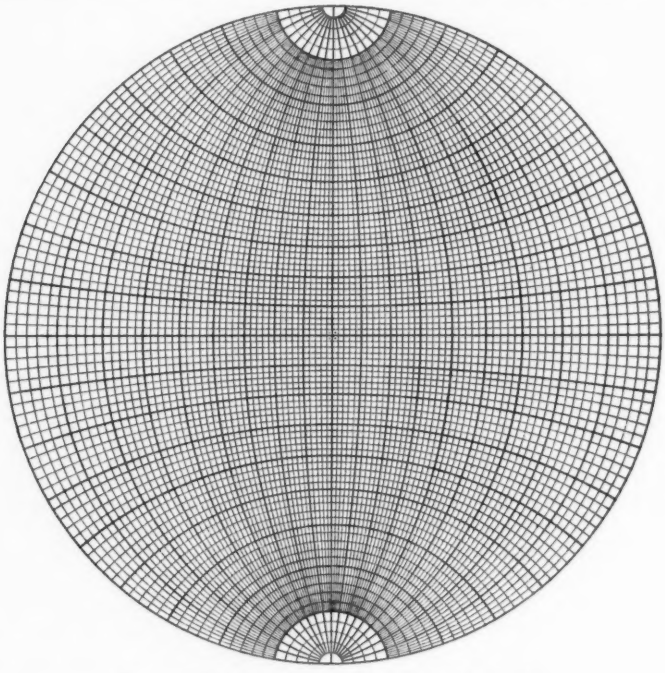

FIG. 1*c*.—Meridian stereonet drawn to 2° intervals

The bearing of a line on the stereogram may be read along the margin of the underlying stereonet. For the line $O'C'$ in Figure 1*b*, for instance, it is $N'C_0$. The plunge—that is, the vertical angle between a line and the horizontal plane—is measured by the angular distance C_0C'. To read it, it is necessary to rotate the stereogram until the line $O'C'$ lies at right angles to the meridional axis of the stereonet; that is, measure the angle along the east-west line of the stereographic net.

A plane is represented in the stereographic projection by the line of strike, drawn through the center O', and the trace of the great circle in which it cuts the hemisphere. In Figures 1*a* and 1*b*, for instance, the plane ACB appears in the projection as the curve $A'C'B'$, of which $A'B'$ is the line of strike. The line $O'C'$, to which reference was made above, shows the direction of dip of the plane.

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lumbia University, at 3 cents each in lots of ten or more.

For other sources, especially of large nets, see Charles S. Barrett, "The Stereographic Projection," *Trans. Amer. Inst. Min. Eng.*, Vol. CXXIV (1937), pp. 29–58.

Fisher's projection protractor can be obtained from the University of Chicago Bookstore at $1.00 each; this shop also sells reprints of the article describing its use (35 cents).

From this it is evident how the projection of a given plane is drawn. On the tracing-paper stereogram, plot first the line of strike, using the graduation on the margin of the stereonet. Then plot the line of dip in its proper direction and length, measuring the angle of dip along the east-west line of the net (having turned the paper into that position), counting the degrees from the margin. Finally trace the meridian that runs through A' and C' to B'.

The practical usefulness of the stereographic projection lies in this graphic representation of vectors and planes in space, without reference to actual location and dimensions. In the following examples, make it a point to see the stereographic diagrams or "stereograms" as three-dimensional pictures of vectors and semicircular planes in space in which the vectors[9]—that is, the radii of the hemispheres—all have unit length.

The directions of the horizontal projections (the bearings) of vectors may be transferred directly on a map by merely placing the tracing paper, on which the stereogram was drawn, on the map, orienting it correctly, with the center over the point of origin for the line that is to be drawn, and transferring the end points of the lines onto the map with a pin prick.

[9] *For a line:* The *trend* in space of a line ("vector") is defined by two angles: the *bearing* of its projection onto the horizontal plane, measured from the geographic north, and the *plunge*, measured from the horizontal in a vertical plane.

For a plane: The "position" in space of a plane is defined by two angles: the *strike*, which is the bearing of the line of intersection of the plane with a horizontal plane (the *strike-line*), and the *dip*, which is the plunge of the line of intersection of the plane with a vertical plane normal to the strike line (the *dip-line*).

For a line within a given plane: The angle which a random line lying within the plane makes with the strike line is called its *pitch*.

The definitions of the terms "plunge" and "pitch" are adopted from Marland P. Billings' *Structural Geology* (New York, 1942).

Similarly, you need not read any directional angle on a map to apply the stereonet to a plane whose strike is shown on the map. Lay the tracing paper directly on the map, oriented accurately with reference to the north direction, and transfer the line onto it.

PROBLEMS NOT INVOLVING ROTATION

Problem 1.—To find the apparent dip of a given bed in a vertical plane that runs in a direction oblique to the strike of the bed.

In Figure 1*b*, $A'C'B'$ represents the given bed. It strikes in the direction $A'B'$ and dips $C'C_0$ degrees. Draw the line DE representing the vertical plane. EF is the apparent dip.

Problem 2.—Find the position in space of the line of intersection of two planes and its map projection.

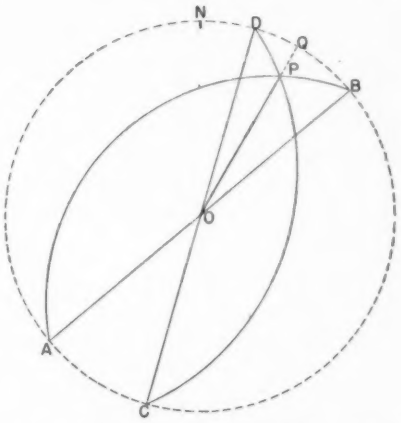

FIG. 2.—Stereogram of two inclined planes (*APB* and *CPD*) and of the line in which they intersect (*OP*).

On tracing paper laid over the stereonet, draw the projections of the two planes (e.g., *APB* and *CPD* of Fig. 2). *OP* is the line of intersection. It plunges *QP* degrees from the horizontal. It bears

NQ degrees east of north. Within the plane APB it pitches BP degrees, and in the plane CPD it pitches DP degrees. This is a lot of information at one stroke; and, what is more, it is directly visualized three-dimensionally in all its implications.

If the line of trend OQ is to be plotted on a map, lay the tracing paper on the map so that the lines AB and CD coincide with the lines of strike on the map and O lies over the point of intersection. With a needle prick, transfer Q onto the map and draw the line.

If specific distances are involved in the problem, get them by trigonometric calculation or an auxiliary construction.

Problem 3.—Find the acute angle of intersection of two conjugate joint planes and the direction in space of its bisectrix (i.e., the direction of maximum shortening of the strain ellipsoid).

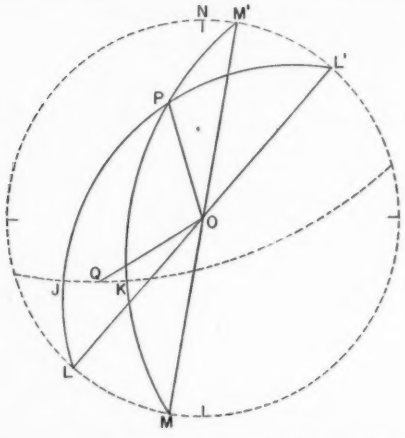

FIG. 3.—Stereogram of two inclined planes (LPL' and MPM'), the line in which they intersect (OP), the angle they form (JK), and its bisectrix (OQ).

On tracing paper placed over the stereonet, plot the projections of the two planes as in Problem 2 (LPL' and MPM', Fig. 3) and find the line of intersection (OP in Fig. 3).

The angle of intersection must be measured in a plane that is normal to the line of intersection. To construct that plane, locate points 90° distant from the line of intersection on LPL' and MPM', namely, J and K. The angle JK is the acute angle of intersection sought. Mark Q, the halfway point between J and K. The line QO gives the position in space of the direction of maximum shortening of the strain ellipsoid.

Problem 4.—Find the position in space of a lineation of given pitch measured on a plane of given dip and strike.

On tracing paper placed over the stereonet, draw the projection of the inclined plane $A'C'B'$ (Fig. 4). On the appropriate side, mark off the angle of pitch of the striations which is measured from the horizontal on the inclined plane, namely, the angle $A'G'$. The direction OG is the bearing of the striations, and the angle GG' is their plunge.

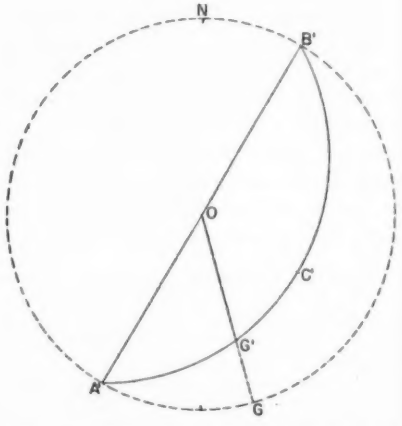

FIG. 4.—Stereogram of an inclined plane ($A'C'B'$) and a line drawn in it that plunges GG' degrees and pitches $A'G'$ degrees.

Problem 5.—An inclined bore hole is to be drilled, plunging S. 60° W., 70° (*OD*, Fig. 5), through slates with cleavage that strikes N. 80° E. and dips 50° to the south (*AEB*, Fig. 5). At what angle will the cleavage appear inclined to the axis when the core is drawn?

As the angle between a line and a plane is measured in a plane perpendicular to the latter, it is necessary, in Figure 5, to draw the normal to the plane *AEB*, namely, *OP*, and find the great circle that runs through *P* and *D*. This cuts the

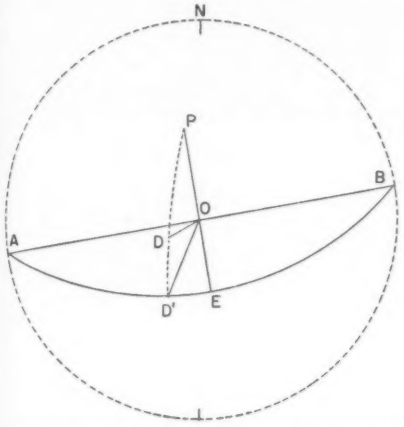

FIG. 5.—Stereogram showing a cleavage plane (*AEB*) and the normal to it (*OP*), an inclined bore hole (*OD*), and the angle it makes with the plane (*DD'*).

plane *AEB* in *D'*. The angle *D'D* is the angle that the axis of the drill core makes with the cleavage.

Actually it is, of course, only necessary to locate point *D*, representing the drill hole, and point *P*, on the prolongation of *EO*, 90° from *E*. The angle *D'D* equals 90° minus the angle *DP*.

Problem 6.—A map (Fig. 6*a*) shows a bed displaced by a fault. The angles of dip of bed and fault and the bearing of slickenside striations on the fault are recorded on the map. What is the length of the net slip (in feet) and its position in space?

Lay tracing paper over the map. Mark on it the *N–S* direction; the lines of strike of fault and bed, indicating on each the direction of dip; and the trend of the

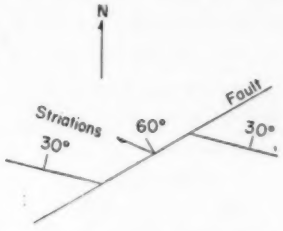

FIG. 6*a*.—Map showing the outcrops of a dipping bed cut by an inclined fault and the projection of slickenside striations on the latter.

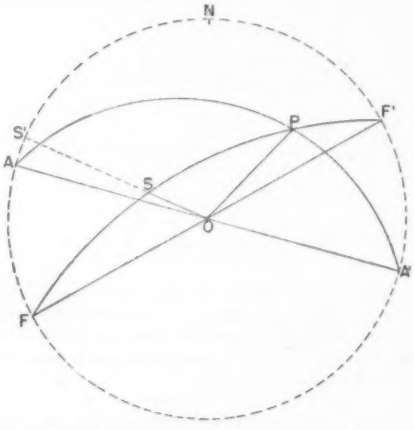

FIG. 6*b*.—Stereogram showing the data derived from the map, Fig. 6*a*, viz., the bedding plane (*APA'*), the fault plane (*FPF'*), and the bearing of the slickenside striations (*OS'*).

striations (*FF'*, *AA'*, and *OS'*, respectively, in Fig. 6*b*). Lay the tracing paper on the stereonet and draw the projections of the two planes (*FPF'* and *APA'*). This gives the answer to the second part of the question, namely, the direction in space of the net slip (i.e., the striations). It plunges *S'S* degrees measured in the

vertical plane $S'SO$ and pitches FS degrees within the plane of the fault.

To help visualize the last step, the directions OS' and OP have been transferred onto the map in Figure 6*c* as dashed lines, labeled $A'S$ and AS, respectively. It is at once obvious that *in the plane of the fault* the net slip $A'S$ is defined by the separation AA' which is

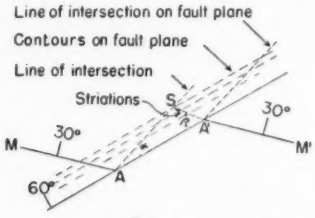

FIG. 6*c*.—The same map as Fig. 6*a* but with the line of intersection of bed and fault plane added to it.

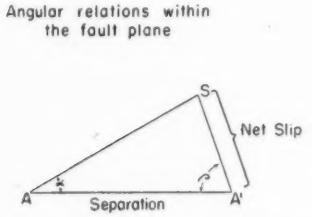

FIG. 6*d*.—Diagram showing the angular relations within the fault plane by means of which the net slip $A'S$ can be constructed graphically (or computed trigonometrically), using the separation AA' and the angles α and ρ.

taken directly from the map, by the angle of pitch of the striations (ρ), and by the angle α, which the line of intersection of fault and bed makes with the horizontal, both of which are taken from Figure 6*b*. A simple auxiliary construction, then, gives the result at once (Fig. 6*d*). AA' is the separation drawn on a scale suitable for the degree of accuracy desired. The angles α and ρ are taken directly from Figure 6*b* ($F'P$ and FS, respectively, read within the plane $FSPF'$). $A'S$ is the net slip, on the scale chosen.

Problem 7.—A map (Fig. 7*a*) shows two veins (*A* and *B*) displaced by a fault. The angles of dip of the two veins and of the fault are recorded on the map. Find

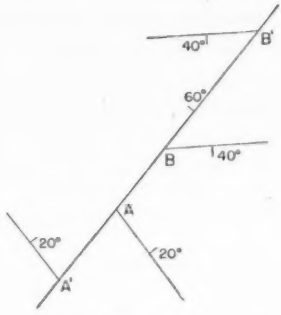

FIG. 7*a*.—Map showing the outcrops of two veins dipping at different angles and cut by an inclined fault.

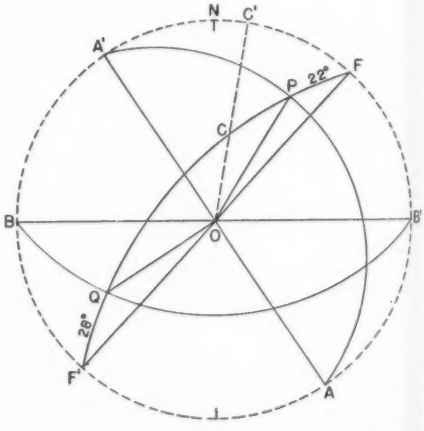

FIG. 7*b*.—Stereogram showing the data derived from the map, Fig. 7*a*, viz., the planes of the two veins (APA' and BQB'), the fault plane ($FPQF'$), the lines of intersection of the fault plane and the veins (OP and OQ), and the direction in space of the net slip (OC).

the length (in feet) of the net slip and its plunge, bearing, and pitch.

Lay tracing paper over the map and mark on it the *N*-direction and the lines of strike of the fault and the beds, all

drawn through one arbitrary point. Transfer the tracing paper to the stereonet and draw the projections of the planes of the veins and the fault (APA', BQB', $FPQF'$, Fig. 7*b*).

Transfer the horizontal projections of the lines of intersection of fault plane and veins onto the map (Fig. 7*c*, $A'C$ and AC', BC' and $B'C$). In Figure 7*c*, C' is the point of intersection of the two veins

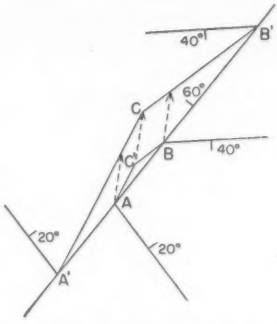

FIG. 7*c*.—The same map as Fig. 7*a* but with the lines of intersection of the beds and the fault plane added to it ($A'C$ and $B'C$, AC' and BC'). $C'C$ is the net slip.

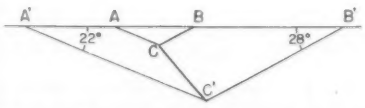

FIG. 7*d*.—Diagram showing the angular relations within the fault plane by means of which the net slip CC' can be constructed (or computed), using the separations AA' and BB' and the angles 22° and 28° taken from Figure 7*b*.

on the foot-wall of the fault, while C is the point on the hanging wall. As the two corresponding points C and C' were originally in contact, CC' is the horizontal projection of the net slip.

To measure the bearing and plunge of the net slip, lay the tracing paper with the stereogram of the fault on the map, with the center coinciding with C and north oriented properly, and transfer the line CC' onto it. This has been done in Figure 7*b*. NC' is the bearing, and CC' the plunge of the net slip.

Its length is obtained by the auxiliary construction shown in Figure 7*d*, drawn in the plane of the fault. The angles 22° and 28° have been obtained from Figure 7*b* (FP and $F'Q$, respectively). CC' is the net slip drawn on the scale of the map.

PROBLEMS INVOLVING ROTATION

Problem 8.—A key bed was perforated by the core drill in two vertical bore

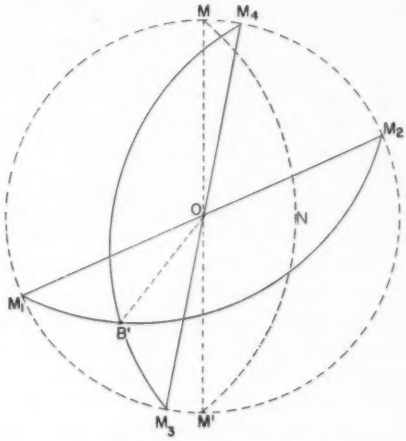

FIG. 8.—Stereogram showing the data used in Problem 8, viz., the direction in space from A' to B' (OB'); the key bed in random orientation (MNM'), showing merely its inclination to the vertical drill core (O); and the same bed rotated about a vertical axis so as to include the line $OB'(M_1B'M_3)$.

holes, at points A' and B', vertically below the surface points A and B which are 500 feet apart. B lies S. 36° W. of A; and the bed was struck 182 feet lower in B than in A, that is, B' lies 182 feet lower than A'. The core of A shows that the beds form an angle of 50° with the axial line of the core. But, as the core was rotated an unknown amount when it was removed from the barrel, its orientation is not known. Find the attitude in space of the key bed, assuming it to be prac-

tically a mathematical plane between points A' and B'.

Proceed in three short steps: (1) By trigonometric calculation or an auxiliary construction, find the angle of plunge of the line from A' to B' (20°). (2) Plot the direction in space, that is, the trend and plunge of $A'B'$ with the aid of the stereonet, on a piece of tracing paper (OB' in Fig. 8). (3*a*) On a second piece of paper, plot the projection of a plane that forms an angle of 50° with the vertical, that is, that dips 40° in any arbitrary direction (e.g., MNM', Fig. 8). (3*b*) Now place the second diagram on top of the first and rotate it until the line OB' comes to lie in the plane MNM', that is, until the great circle MNM' runs through B'.

Two positions are found that satisfy the condition, namely, $M_1B'M_2$ and $M_3B'M_4$. Which one is correct must be decided on other evidence, such as, for instance, a third bore hole.

Step 3*a* is really unnecessary and was introduced above only to assure a clear visualization of the procedure. Instead of rotating a separate piece of tracing paper until the two 40° circles drawn on it run through B', simply rotate the original stereogram until B' lies at its two possible positions above either one of the 40° great circles of the stereonet.

Problem 9.—The same as Problem 8 but with the second drill hole slanting. In this case, a key bed which was cut at a point A' in the drill hole A was penetrated at a point B' in drill hole B. This second hole had become crooked, so that at the point B' where it struck the key bed it plunged 30°, S. 80° W. When the core was pulled, the bed was found to be inclined 30° to the core's axis. Find the bed's attitude in space, assuming the true position of B' to be known and no record to have been kept of the vertical drill hole A other than the depth to the key bed.

1. The first step is the same as in Problem 8, finding the plunge of the line $A'B'$. 2. Now plot, on tracing paper placed over the stereonet, (*a*) the projection of the vector $A'B'$ (OB of Fig. 9*a*); (*b*) the projection of the attitude in space of the core's axis as recorded at point B' (OD in Fig. 9*a*).

Now look at Figure 9*a* and see it three-dimensionally. The next step will suggest itself readily. We can imagine the whole hemisphere, of which Figure 9*a* is the stereogram with the points D and B on it, turned in such a manner that the axis of the drill hole, that is, OD, comes to stand vertically. In order to do this constructionally, draw a horizontal line at right angles to OD (line RR' in Figure 9*b*). This is the axis about which the hemisphere (seen in projection) must be rotated in such a way that D goes to the position of O. When the tracing paper with the plot of Figure 9*b* is placed on

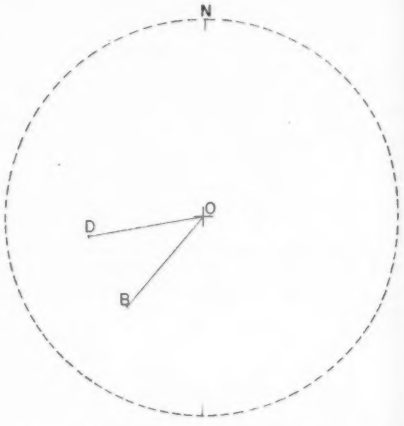

FIG. 9*a*.—Stereogram of the two directions in space with which Problem 9 is first concerned, viz., that of a line drawn from A' to B' (OB) and that of the inclined axis of the drill hole (OD).

the stereonet in such a way that RR' lies over the N–S line, it is seen readily that, when the hemisphere is turned about RR' as axis, every point on it travels along the lines of parallels,[10] of which a few have been represented as dotted lines in Figure 9*b*. Each point moves, of course, through the same angle as point D, that is, the angle DO. As the hemisphere is turned and D moves to O, point B moves to the position B' shown in Figure 9*c*. In

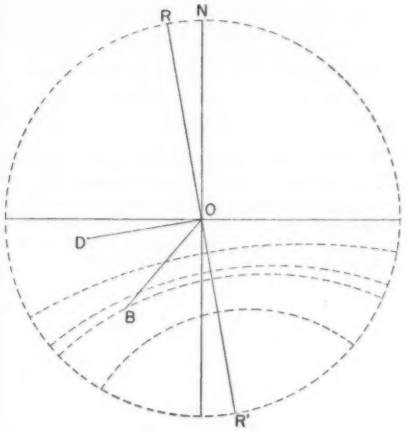

FIG. 9*b*.—The same as Fig. 9*a* but with the addition of the axis of rotation (RR') and several parallels of rotation, including the one along which B will travel, while D moves to O.

this figure the axis of the core stands vertical.

We know that the key horizon is inclined to that axis at an angle of 30°. The next steps are now identical with steps 3*a* and 3*b* of Problem 9; that is: (*a*) On a separate piece of tracing paper, plot the projection of a plane inclined 30° to the vertical (60° dip) in any arbitrary position (e.g., M_oEM_o in Fig. 9*d*). (*b*) Place this diagram on top of the first one and

[10] See Fig. 1*c*. On the reference sphere the parallels run parallel to the equator, i.e., at right angles to the meridians.

turn it until the position is found in which the projection of the plane M_oEM_o

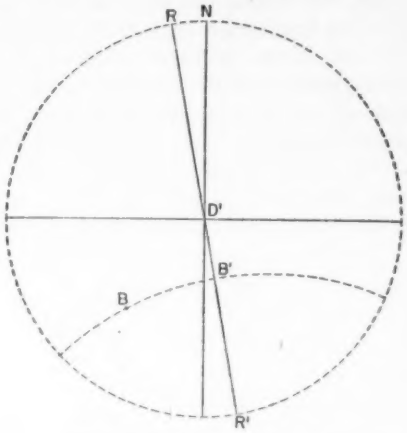

FIG. 9*c*.—Stereogram showing the axis of rotation RR' and the point B in its original position (both as in Fig. 9*b*) with the position B' after rotation added.

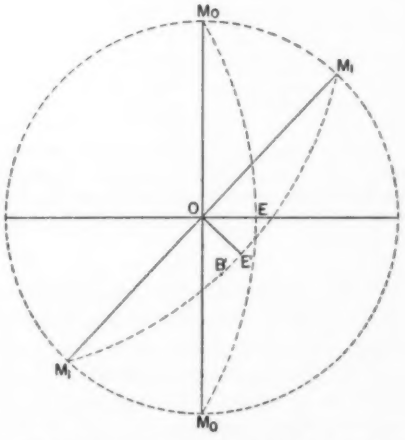

FIG. 9*d*.—Stereogram showing point B in its new position B'; the key bed in random orientation (M_oEM_o), showing merely its inclination to the now vertical drill core (O); and the same bed rotated so as to include $B'(M_1B'M_1)$ (one of two possible positions).

passes through the point B' on the lower diagram. Of the two possible posi-

tions, only one is shown in Figure 9*d* ($M_1E'M_1$).[11]

All that remains to be done is to rotate the hemisphere back to its original position, shown in Figure 9*b*. In Figure 9*e* the position of the key bed, $M_1E'M_1$, determined in the preceding step, is shown in dashed lines (OE', marking the dip line, and OF', an auxiliary construction line drawn in the key bed at any convenient position). The axis of rotation RR' is also drawn in dashed lines. Other dashed lines mark the parallels along which the points $O = D'$, B', E', and F' travel as the hemisphere is rotated so as to bring D' and B' back to their original positions D and B (the same as in Fig. 9*b*). This rotation carries E' to E and F' to F. The points F, E, and B, however, define the key bed. Find the great circle that passes through F, E, and B, and you have one of the two possible positions of the key bed in space, M_2EFM_2.

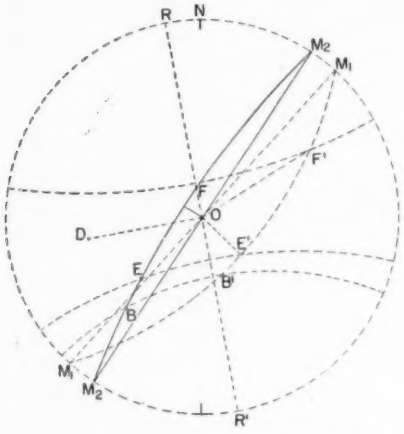

FIG. 9*e*.—Stereogram showing the plane $M_1B'M_1$, the axis of rotation RR', the parallels of rotation along which the points B', E', F' travel to the positions B, E, F, and the plane M_2BEFM_2, defined by the latter.

Problem 10.—An inclined bore hole is drilled so as to intersect an inclined vein. Assume the vein to have the shape of a plane and the bore hole that of a straight line. At what horizontal distance from the mouth of the bore hole and at what depth will the drill cut the vein?

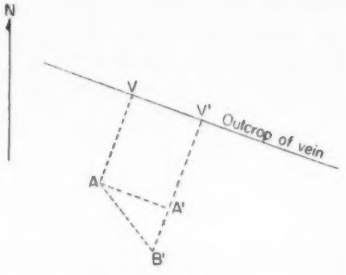

FIG. 10*a*.—Map showing the outcrop of a vein (VV'), the mouth of an inclined borehole (A), the upward projection B' onto the horizontal surface of the point (B) at which the borehole intersects the vein at depth, and a point A' on the surface which is the projection of A onto the line $V'B'$.

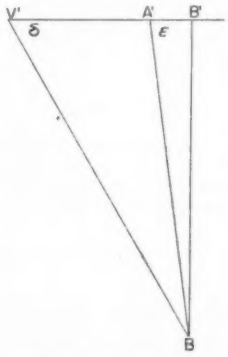

FIG. 10*b*.—Vertical cross-section through the points V', A', B', and B shown on the map, Fig. 10*a*.

Such a case is shown on the map, Figure 10*a*. A is the mouth of the bore hole;

[11] As in Problem 8, one will use, in general, the simpler process of rotating the stereogram of OB' ($= D'B'$ in Fig. 9*c*) over the stereonet until B' comes to lie above either of the two great circles that are inclined 30° to the vertical.

B, the point of intersection of bore hole and vein at depth; B', a point on the surface vertically above B; and $V'B$, an inclined line drawn on the vein from the point of intersection to the outcrop, at right angles to the strike of the vein.

Figure 10*b* shows a hypothetical cross section drawn vertically through the points V', A', and B'. In it only the distance $V'A'$ $(= VA)$ and the angle of dip, δ $(B'V'B)$, are known. But the angle ϵ $(B'A'B)$ can be determined, and with it the cross section can be constructed to scale. Proceed as follows:

On tracing paper above the stereonet, plot the vectors of the bore hole and of the dip of the vein (OP and OD, Fig. 10*c*). Now imagine the hemisphere, of which the stereonet is the projection, rotated 90° about the direction of the dip

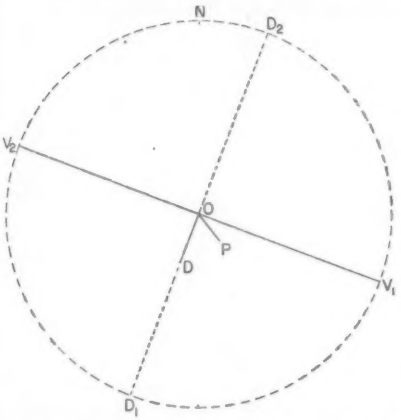

FIG. 10*c*.—Stereogram showing the directions in space of the bore hole (OP) and the dip (OD) and strike (V_1V_2) of the vein.

of the vein as axis (D_1D_2), so that V_1 comes to lie vertically below O (Fig. 10*d*). You now see all the vectors projected on a plane normal to the strike. D has come to lie on the periphery of the net at D_0 (Fig. 10*d*); and the angle D_1D_0 is δ, the angle of dip of the vein. The point P correspondingly has come to lie at P_1, and D_1P_0 is the angle ϵ sought.

In actual practice, only P, D_1, and D_2 need be plotted, giving P_0 and the angle ϵ in less than a minute.

An auxiliary construction (Fig. 10*b*) gives $B'B$, the depth at which the bore hole strikes the vein, and $V'B'$. Plotting

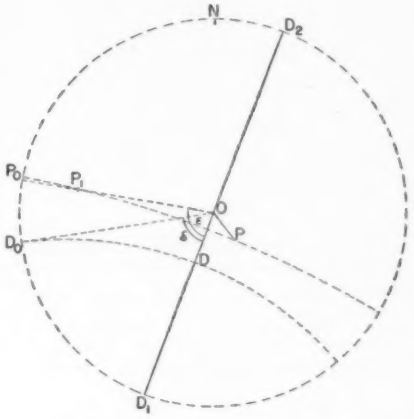

FIG. 10*d*.—Stereogram showing the parallels along which the points P and D travel to the new positions P_1 and D_0 as rotation takes place about D_1D_2 as axis. The angles δ and ϵ are the same as in Fig. 10*b*.

the latter distance on the map secures the horizontal distance AB'.

Problem 11.—A map (Fig. 11*a*) shows inclined beds (A) below differently inclined beds (B) beneath an unconformity. Find the dip and strike of the beds A when the beds B are restored to a horizontal position.

On tracing paper laid over the stereonet, plot the planes A and B (APA' and BQB', respectively, in Fig. 11*b*, where P and Q mark the directions of the dip). On the plane APA' choose one or more conveniently located points—for example, S and T. Then imagine the whole rotated with BB' as axis of rotation until

the plane BQB' lies horizontally. When that has been achieved, as in Figure 11*c*, Q has come to rest on Q', QQ' being the angle of rotation. The points P, S, and T have rotated along the parallels for which

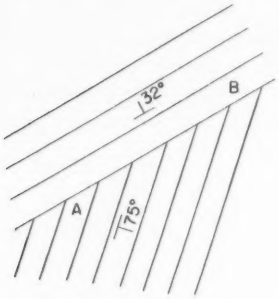

FIG. 11*a*.—Map showing inclined beds (A) below differently inclined beds (B) beneath an unconformity.

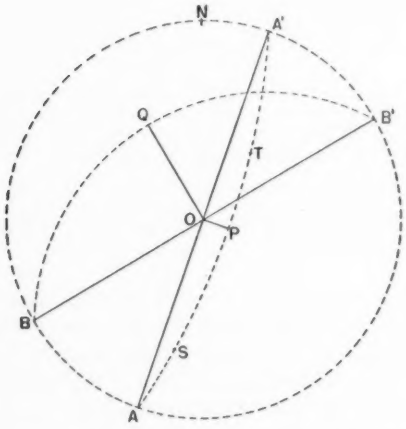

FIG. 11*b*.—Stereogram showing the beds A and B of Fig. 10*a* (APA' and BQB', respectively) with their respective dip lines (OP and OQ).

BB' is the axis (indicated by dotted lines on Fig. 11*c*) and have reached the positions P', S', and T'. The result is shown in Figure 11*d*, where A_1A_2 represents the strike and P_1P_2 the dip of the beds A after the beds B have been restored to a horizontal position.

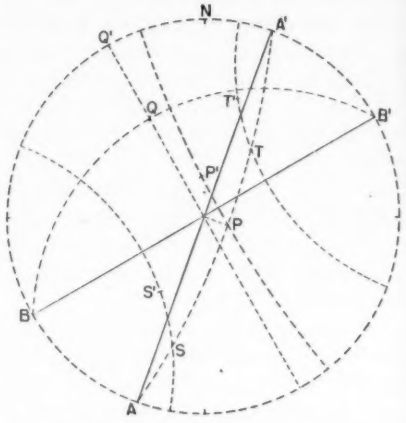

FIG. 11*c*.—Stereogram showing the same planes as Fig. 11*b*, with the parallels added along which points P, Q, S, T travel to new positions P', Q', S', T' as the whole is rotated about BB' as axis.

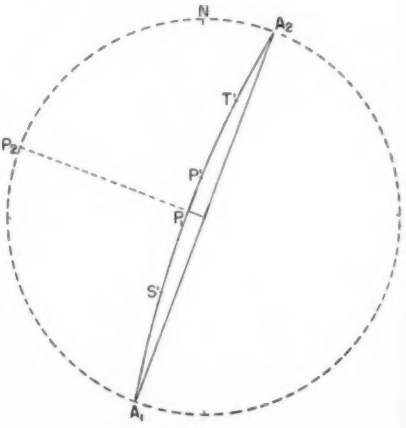

FIG. 11*d*.—Stereogram showing the points P', P_1, S', and T' derived in Fig. 11*c* and the plane defined by them ($A_1S'T'A_2$).

Problem 12.—A fault that strikes N. 10° E. and dips 60° east has cut across horizontal beds (Fig. 12*a*). The movement on the fault was rotational, one

side having rotated through an angle of 20° about an axis perpendicular to the fault in such a way that in the part south of point P the east side was depressed below the original level. What is the strike and dip of the beds on the downthrown side?

To visualize this, turn Figure 12*a* in such a way that the fault plane lies horizontal. Then the right-hand block (which has been rotated) appears to stand in an inclined position on the (now horizontal) fault plane. In that position the rotation is seen to consist merely in turning the inclined block 20° about a vertical axis.

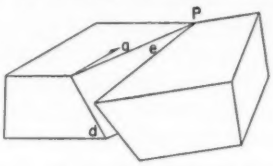

FIG. 12*a*.—Block diagram showing rotational fault.

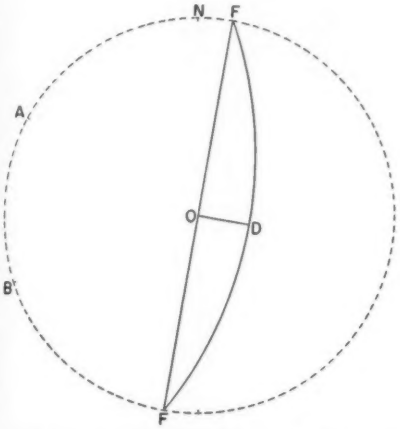

FIG. 12*b*.—Stereogram showing the fault plane (*FDF*) and the horizontal bedding plane (*FABF*).

Correspondingly, proceed by the following steps:

1. Plot the fault plane on tracing paper above the stereonet and choose two arbitrary points in the horizontal plane, that is, on the margin of the net opposite the projection of the fault plane (e.g., *A* and *B*, Fig. 12*b*).

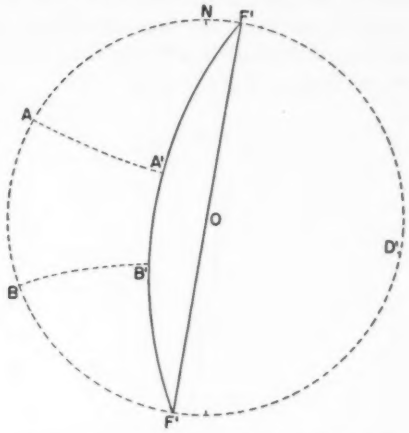

FIG. 12*c*.—Stereogram showing the result of rotation about *F'OF'*. The fault plane is now horizontal (*F'D'F'*) and the bedding plane inclined (*F'A'B'F'*).

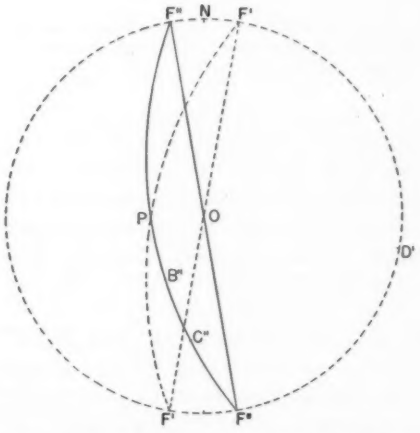

FIG. 12*d*.—Stereogram showing result of rotation of *F'PF'* about a vertical axis into new position *F"PF"*.

2. Imagine the fault plane rotated about its strike (*FF*, Fig. 12*b*) to a horizontal position. Such a rotation carries

D to D' on the margin of the projection and points A and B of the originally horizontal bedding plane to the new positions A' and B' (Fig. 12*c*). The plane that passes through these points A' and B' dips (of course) in the opposite direction to that of the fault plane, the same number of degrees (60°).

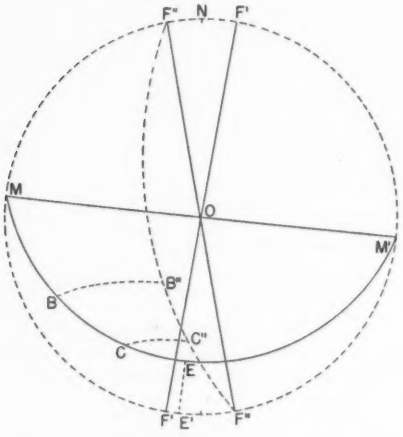

FIG. 12*e*.—Stereogram showing result of rotation about $F'OF'$. The plane $F''B''C''F''$ assumes the position $MBCM'$.

3. Rotate bedding plane ($F'A'B'F'$) about a vertical axis through 20°. This can be done either to the right or to the left (Fig. 12*d*). Be sure to do it in such a way that the southern half of the bedding plane is carried below its original position, that is, so that F' reaches the position F'' in Figure 12*d*.

The two planes $F'PF'$ and $F''PF''$ represent the strata on opposite sides of the fault as seen when viewed at right angles to the latter. $F'PF'$ represents the horizontal beds, and $F''PF''$ the tilted beds. When the hemisphere is turned back to its original position, the northern half extends above the plane of the paper. The point A' can therefore not be used in that process and has been omitted from Figure 12*d*. As two points will be needed to define the plane $F''PF''$ when the hemisphere is turned back to its original position, a second arbitrary point must be chosen in the southern half of $F''PF''$—for instance, C''.

4. Rotate the whole hemisphere about $F'F'$ as axis so that the fault plane ($F'PF'$) is returned to its original position. This carries the points B'' and C'' to new positions B and C (Fig. 12*e*). Find the great circle that runs through B and C. It defines the attitude of the beds on the downthrown side: the angle MM' is their strike, and $E'E$ their dip. Transfer strike and dip onto the map. The result is shown in Figure 12*f*.

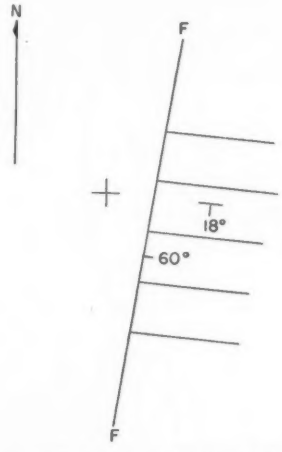

FIG. 12*f*.—Geologic map showing the fault, horizontal beds on the west side, and dipping beds on the east side, after rotation.

Problem 13.—A geologic map (Fig. 13*a*) shows dipping beds cut by a hinge fault similar to the one illustrated in Figure 12*a*. The beds on the (undisturbed) upthrown side strike N. 46° E. and dip 20° northwest, while those on the downthrown side strike N. 15° E. and dip 16° northwest. How large is the

angle *e* through which the beds on the downthrown side have been pivoted?

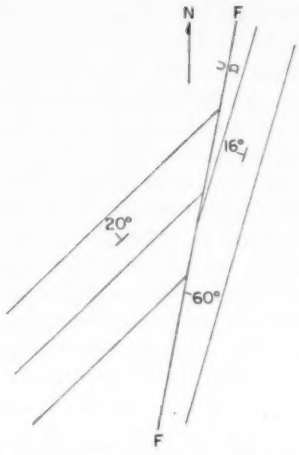

FIG. 13*a*.—Geologic map showing a rotational fault on opposite sides of which the beds have different dip and strike.

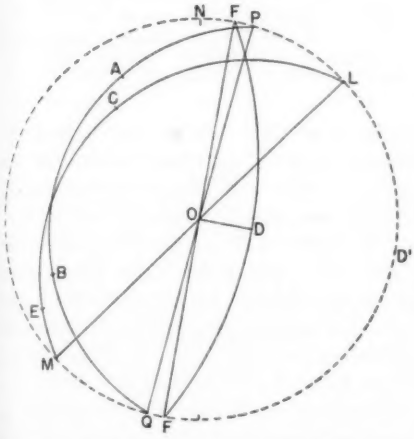

FIG. 13*b*.—Stereogram showing the fault (*FDF*) and the two bedding planes (*LCEM* and *PABQ*) of Fig. 13*a*.

Proceed as follows:

1. On tracing paper above the stereonet, plot the two bedding planes and the fault plane (*PABQ*, *LCEM*, and *FDF*, respectively, in Fig. 13*b*).

2. Imagine the reference sphere rotated about *FF* as axis until the fault plane is horizontal. This carries *PABQ* to the position *P'A'B'Q'*, and *LCEM* to that of *L'C'E'M'* (Fig. 13*c*). The angle *P'L'* is the angle of rotation *e*.

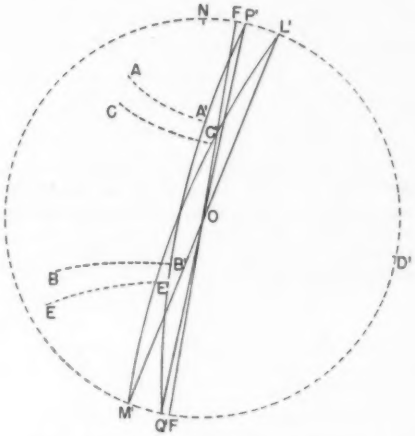

FIG. 13*c*.—Stereogram showing the result of rotation: the fault plane now horizontal (*FD'F*) and the two bedding planes in the new positions *L'C'E'M'* and *P'A'B'Q'*.

Problem 14.—Two drifts, inclined at different angles in different directions, run past each other in a mine, some distance apart. What is the attitude in space of the shortest distance between them, and where is it located with reference to the entries of the two drifts?

Such a problem is not likely to be encountered in ordinary mining practice. It is introduced here only because it illustrates especially well the manner in which the use of the stereographic projection leads to visualization of the essential elements of a three-dimensional problem.

The shortest distance between two random lines in space lies in that direc-

tion which intersects both lines at right angles. Figure 14*a* shows two such drifts in map projection. The bearing of each drift is given by the map; and from the elevations of the end points the plunge of AA' is found to be 26° to the northwest,

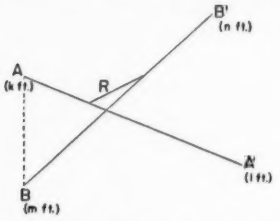

FIG. 14*a*.—Map showing two drifts (AA' and BB'), one above the other. Both are strongly inclined, the elevations of the end points being given in feet. The line R marks the direction of the shortest possible connection between the two drifts, but not its actual position.

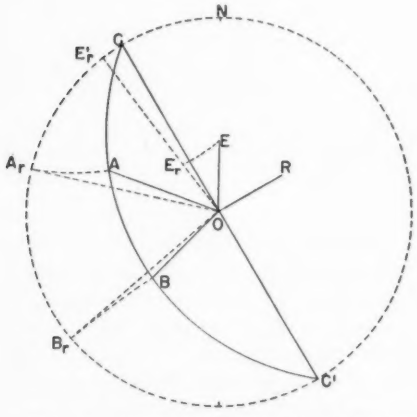

FIG. 14*b*.—Stereogram showing (1) the directions in space of AA' and BB' of Fig. 14*a* (OA and OB); the plane ($CABC'$) that includes OA and OB and the normal to it (OR); and the direction in space OE of BA of Fig. 14*a*; (2) the results of rotation, carrying R to O, A to A_r, B to B_r, and E to E_r.

of BB', 38° to the southwest. Plot the two space directions on tracing paper above the stereonet (OA and OB, Fig. 14*b*) and find the plane that is defined by the points A and B ($CABC'$, Fig. 14*b*). The normal to that plane is normal to both AA' and BB' (OR, Fig. 14*b*). The bearing and plunge of OR is that of the shortest distance between AA' and BB', answering the first part of the question. In Figure 14*a* this direction has been added to the map picture (R) without regard to its true location.

Looking in the direction of R (Fig. 14*a*), we would be looking vertically down on the two drifts. Figure 14*c* shows diagrammatically what we would see. To distinguish the points as they appear in this "R"-projection, we shall attach the

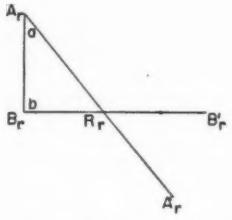

FIG. 14*c*.—Diagram showing the lines of Fig. 14*a* projected onto a plane normal to R (the R-projection). $A_rA'_r$ and $B_rB'_r$ are the true lengths of the two drifts on the scale of the diagram. A_rB_r is the projection of the inclined line AB.

suffix r to their letters, so that A_r in Figure 14*c*, for instance, indicates the entry A of one of the drifts, shown in Figure 14*a*, as seen in the R-direction.

In Figure 14*c*, as stated above, the lines $A_rA'_r$ and $B_rB'_r$ lie in two planes that are parallel with each other and with the paper, one vertically above the other, so that the line A_rB_r slopes down from B_r to A_r. The point R_r marks two points, one vertically above the other, the end points of the line of shortest distance R between the two drifts. The distances A_rR_r and B_rR_r represent the true distances from the entries A and B to the R-points on the scale of the diagram. The distance A_rB_r is the R-projection of the distance AB. We can determine it

and the angles a and b and with the aid of these three quantities construct the triangle $A_rB_rR_r$ and thus find the distances A_rB_r and B_rR_r.

To determine the distance A_rB_r, proceed as follows:

1. Using the map distance AB and the elevation of B over A, given on the map, compute or construct graphically the true length of AB and its plunge. Enter the vector of AB (bearing and plunge) into the stereogram (OE, Fig. 14b).

2. Rotate the hemisphere of which 14b is the stereogram, so that the vector OR is brought into a vertical position, that is, so that R coincides with O. This causes E to move to E_r. The angle E'_rE_r is the plunge of the line AB as seen in the R-projection, that is, in Figure 14c.

3. From the length AB and the plunge E'_rE_r just determined, compute or construct graphically the length A_rB_r.

The angles a and b can be read directly from Figure 14b. We obtained them when we rotated the hemisphere. Remember that OA and OB represent the true directions in space of AA' and BB', respectively. By turning R into the vertical position, OA and OB were turned into the horizontal positions OA_r and OB_r. These are the directions of the two lines in the R-projection. Comparing Figures 14b and 14c, we can read directly: Angle a in Figure 14c is the angle E'_rA_r in Figure 14b. Angle b in Figure 14c is the angle E'_rB_r in Figure 14b.

With the aid of A_rB_r and these angles the distances A_rR_r and B_rR_r can now be constructed or computed.

FINAL COMMENT

In the solution of all the problems discussed in this paper separate drawings have been given for every essential step involved, and all great circles defining planes have been drawn out in full. As the geologist becomes familiar with this use of the stereographic projection, he will learn quickly to combine all operations in one drawing. After a few trials he will confine himself to putting only essential points and only such sections of circles on the paper as are needed in the construction. In Problem 1, for instance, only one-half of the line DE (viz., $O'E$) and the intercept F need to be drawn. In Problem 11 one puts on the tracing paper only the following marks: two points, S and T, chosen arbitrarily along the great circle representing the plane APA' (which need not be drawn); two additional points, S' and T', marking the positions of S and T after rotation; and finally the points A_2 and P_2, marking the strike and dip of the plane APA' after rotation—a total of six points.

ACKNOWLEDGMENTS.—The writer is indebted to Drs. C. I. Lubin, University of Cincinnati, and D. Jerome Fisher, University of Chicago, for reading the manuscript and suggesting improvements in the mode of presentation. He owes special thanks to Dr. Fisher for critical editorial advice, helpful discussion of terms, and several references incorporated in footnotes 5 and 8.

APPENDIX

D. JEROME FISHER

After reading Professor Bucher's article, attention was called to the possibility of doing some of the problems in simpler fashion. Dr. Bucher suggested that these be pointed out in an appendix, stating that he regarded his treatment as superior for the beginner, for whom the paper was prepared. I sincerely thank Dr. Bucher for his courtesy.

In order to simplify certain problems, it is necessary to substitute a line for a plane; this means that a one-dimensional concept replaces a two-dimensional one. This can be done, since through any giv-

en point it is possible to erect only one line normal to a plane.

In general, Dr. Bucher shows a plane by the arc of a circle; this arc represents the projection of *that* circle on the basic sphere which is given by the intersection of the plane (passing through the center of the sphere) with the spherical surface. Such a method of representation is direct or nonreciprocal, and it yields the cyclographic projection of the plane. If we substitute for this plane a line normal to it through the center of the basic sphere, we obtain a point on the spherical surface which, of course, is projected as a point in the stereogram. This projected point represents a reciprocal projection of the plane, and this is known as the "stereographic projection" of the plane.

Thus, in Figure 1*a* the plane *ACB* cutting the center of the basic sphere is projected cyclographically to the arc *A'C'B'* in the stereogram shown in perspective below it (the actual stereogram appears as Fig. 1*b*). Similarly, in Figure 5 a plane is projected cyclographically onto the stereogram by the arc *AEB*. However, in this figure the point *P* is the stereographic projection of the same plane, since the line *OP* is the projection of a line in space normal to the plane through the center of the basic sphere. *P* is called the pole of the plane, because *P* is 90° distant from every point on the arc *AEB* (just as on the globe either pole is 90° from every point on the equator).

Following this introduction are given stereographic solutions of some of the problems which Dr. Bucher worked cyclographically. In general, these can be done more expeditiously by using the combination of stereoscale and stereonet available on the Fisher projection protractor. However, keeping in mind the simplicity desirable for the beginner, they are all done by means of the stereonet alone, in the fashion made clear by Dr. Bucher.

Problem 11.—The two-tilt problem. The lower beds (*A* of Fig. 11*a*) dip 75° to S. 70° E. Visualize this plane cutting the center of the sphere *O*. A normal to this plane through *O* will then cut the lower hemisphere in a point whose stereographic projection is *L* in Figure 15. The latter point may be called a "face-pole," by analogy with crystallography, where

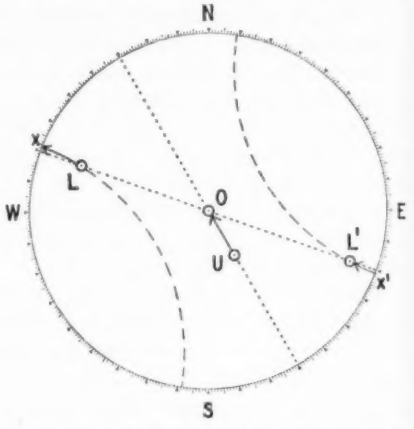

FIG. 15.—Stereogram of the two-tilt problem (No. 11). *U* represents a normal to the upper beds (*B*'of Fig. 11*a*), and *L* is one to the lower beds (*A* of Fig. 11*a*), both after the second tilt. Corresponding points just before the second tilt are *O* and *L'*.

the projected point representing a normal to a crystal face (a plane) is so designated. Point *L* is located by rotating the tracing-paper stereogram (Fig. 15) above the stereonet until the radius bearing N. 70° W. lies above either the polar or equatorial axis of the net and by counting in along this 15° from the divided circle. The line *OL* need not be drawn. Likewise, the normal to the upper beds (*B* of Fig. 11*a*), dipping 32° to N. 30° W., will cut the lower hemisphere in a point whose stereographic projection is *U* (Fig. 15); this is located in similar fashion as a

point; there is no need to draw the line *OU*, and, in actually doing the problem, an experienced worker would not even bother to locate point *U*. After marking *L*, he would simply rotate the stereogram above the stereonet until the diameter N. 30° W. (dip of the upper beds) lay above the equator of the net. It would then be clear that, to make a point such as *U* move to *O*, which is equivalent to having the upper beds become horizontal, it would be necessary similarly to move point *L* along a small circle of the net through 32°. After point *L* goes 19½°, the divided circle is reached at *x;* thus continue 12½° along the corresponding small circle from the diametrically opposite point on the divided circle at *x′*, giving point *L′*. The small circle along which *L* migrates is shown by dashed lines in Figure 15; but, of course, this would not be drawn in actual practice. Thus, the normal to the lower beds before the second tilt is projected as point *L′*. Rotate the stereogram until this point lies above the polar or equatorial axis of the stereonet and read the answer, which is dip *L′O* degrees in the direction *L′O* (and *not* in the direction *OL′*).

The most important reason for utilizing the stereographic projection in solving problems is that the worker can readily visualize every step of the procedure. Unless one does this, he might better use nomograms, tables, or formulas. If the beginner has difficulty in getting a three-dimensional concept from Figure 15, he should cut the ends off a number of tooth picks, so that the portions left are each the same length as that of the radius of the divided circle of the figure. Stick one of these into a small ball of plasticine and hold it vertically above *O* of the figure, with the ball at the top. Then point *O* is the projection of the free end of this toothpick, which is supposed to lie at the south pole of the basic sphere. Stick another toothpick in the ball aiming toward a point on the S. 30° E. radius about twice as far out from *O* as is *U*. This toothpick will make an angle of about 32° with the first one. The stereographic projection of the free end of this toothpick is at *U* of Figure 15. (This would perhaps be clearer had the plane of projection of Figure 1*a* been taken as the equatorial plane of the basic sphere rather than as a parallel plane below the sphere; however, the only difference is one of scale.) Now stick a third toothpick into the ball, pointing in the direction *OL* but dipping only 15°. Lastly, stick a fourth toothpick into the ball which is diametrically opposite the third one. The free ends of the "spines" on this echinoid-like ball represent points on the surface of the basic sphere. Hold the ball between the thumb and a finger of the left hand directly above *O* of Figure 15, with the first toothpick pointing toward *O*, the second in a direction S. 30° E. with a dip of 58°. Now rotate the ball on an axis normal to *OU*, so that the free end of the second toothpick comes to lie above *O*. The first toothpick will point N. 30° W. at a dip angle of 58°, and the end of the fourth toothpick will locate a point whose projection is *L′*. Once having gone through this exercise, no one should have undue difficulty in seeing in three dimensions of the mind while looking at a stereogram.

Problem 12.—Given an inclined rotational fault, as in Figure 12*a*. Find the dip of formerly horizontal beds after a 20° rotation (anticlockwise, looking downward and westerly, normal to the fault plane).

Assume a fault plane that dips 60° to S. 80° E. Its face-pole would thus appear

at F, Figure 16. If the fault plane is made horizontal (F goes along the dashed line to O), then the face-pole of the horizontal beds moves from O to L, where FOL is a straight line and $OF = OL$. Rotate L anticlockwise about O through 20°. This

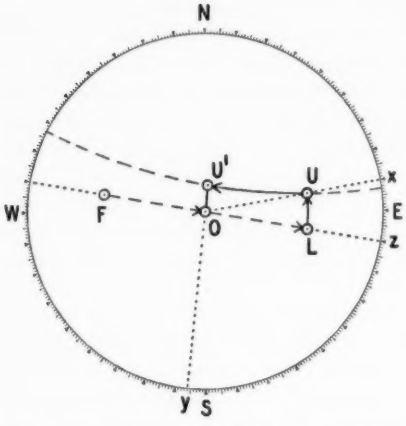

FIG. 16.—Stereogram of the first rotational-fault problem (No. 12, Fig. 12*a*). The fault F cuts horizontal beds O. When the fault is made horizontal (F goes to O), the face-pole O, representing the normal to the horizontal beds, moves to L. The latter, rotated 20° about O, gives U; this moves to U' if F returns to its original position. The faulted beds that become tilted thus dip $U'O$ degrees toward Oy.

can be done with a compass; but, when working above a stereonet, it is simpler to rotate the stereogram until the radius Ox (which is 20° from Oz) lies above the equator of the stereonet and to lay off $OU = OF = OL$. In this position, if L is moved back to O, U must go to U'. The answer is thus $U'O$ degrees in the direction $U'Oy$.

Problem 13.—Given a series of monoclinal beds dipping 20° to N. 41° W., as is shown in Figure 13*a*. This is cut by a rotational fault dipping 60° to S. 80° E. The beds on the west side remain undisturbed; those on the east side assume a dip of 16° to N. 75° W. What is the angle *e* through which the beds on the east side have been pivoted about an axis normal to the fault plane?

Plot in the stereogram Figure 17 the face-poles representing the fault F and the two sets of dipping beds, D for those on the downthrown or east side and U for those on the upthrown or west side. Rotate the stereogram until F lies above the equator of the stereonet. Then, if F is moved to O (dashed line), it means D and U must migrate along small circles (dashed lines) through the same angular distance of 60° to D' and U'. Radii through these last two points cut the

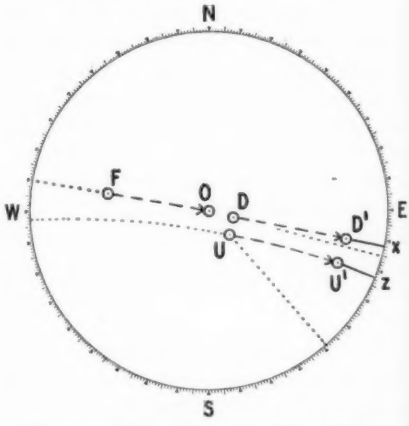

FIG. 17.—Stereogram of the second rotational-fault problem (No. 13, Fig. 13*a*). The fault F cuts beds dipping U on its west (upthrown) side and D on its east (downthrown) side. The actual rotation about an axis normal to the fault plane is xz.

divided circle at x and z. The angular distance between these two points, read directly off the divided circle, is the desired angle e. In the particular case taken for this example, the angle e is practically identical with the actual angle between the two sets of dipping beds.

REVIEWS

Geomorphology, Systematic and Regional. By O. D. VON ENGELN. New York: Macmillan Co., 1942. Pp. 655; figs. 372. $4.50.

This book, by a professor of geology in Cornell University, is the best text in English to give a summary and critical discussion of the German school of which Walther Penck was the most forceful voice. But Professor von Engeln's work is also representative of the so-called "American school," a school which deals principally with the classification of land forms and might therefore be better termed the school of "land-form classification." Despite the title, the book is primarily a *systematic* approach, the regional discussions being largely confined to one chapter—"The History of the Folded Appalachians."

This book will serve excellently as a reference dictionary or encyclopedia of geomorphic terms for students of all levels from the elementary to the most advanced. Indeed, so much space is given to the presentation of terms from both English and other sources that the descriptions of processes are frequently too brief. There is a commendable emphasis upon the cycle of erosion concept, which guides the author in the organization of much of the book.

Geomorphology, Systematic and Regional, will not, however, prove satisfactory as an elementary textbook, nor is it, in this reviewer's opinion, a book for even the earlier advanced courses in geomorphology. While no one can question the symmetry and scientific usefulness of the broad and simplified regional generalizations and descriptions characteristic of the American "land-form classification" school, their place in geomorphology is still further along the course of graduate studies where such simplification will not be misleading. When elementary students are expected to absorb such simplified concepts and are led to believe that in them they possess a definite knowledge useful in subsequent courses, in other geologic work, or to prevent boredom in later life, the results are likely to be bad. University students, and even those graduate students in American schools who have neither traveled extensively nor done geologic field work, do not have a grasp of the simpler, more local, and more fundamental concepts of physical geology with which to correlate and so *use* regionally simplified concepts with satisfaction or profit. Such is true, in other fields of thought, of the larger American educational scene.

Perhaps the most serious weakness of this work, and equally of other writings of the American school, is the frequent application of the terms "consequent" and "subsequent," with genetic or historical connotations to streams and valleys of the most obscure origins. No one can quarrel with the label "consequent" when it is applied to certain streams "because they . . . . flow in consequence of the original inequalities of the surface" (p. 111), for certain streams on topography of a strictly surficial origin doubtless took their course on that original surface. On most of the earth's surface, however, streams have cut their valleys in rocks which were tectonically disturbed at extremely slow rates and at times vastly remote in comparison with the origins of such strictly surficial features as terminal moraines, lake plains, flood plains, and many volcanoes. To classify streams as consequent (on the original surface) or subsequent (because they "follow after the consequent stream and valley in development" [p. 118]) without the most exhaustive study of the local geologic history is indeed scientifically hazardous. The author repeatedly qualifies his use of these terms yet continues to employ them apparently with historical meaning.

In the discussion of the Jura, and elsewhere, von Engeln points out that "the present cycles of erosion of fold-mountain units were commonly begun on structures previously more or less completely beveled across" (p. 314). This is unquestionably true also of most of the structural units in the tectonically deformed plains of North America and probably of the entire world. Yet he uses the terms "consequent" and "subsequent" apparently with a time connotation as though they were being applied to first-cycle erosion instead of using them with a purely structural connotation. An unnecessary element of confusion is thus introduced into a most useful book.

Chapter vii, "The Normal or Fluvial Geo-

morphic Cycle on a Coastal Plain," does little better, for the hypothetical normal cycle is presumably a first cycle. First-cycle coastal plains must be rare on this planet, if one may judge from the broadest so-called "coastal plain" in North America—the western Gulf Coastal Plain. Even the youngest bedrock formation of this region, the Beaumont of Pleistocene or Recent age, in spite of its fossil natural levees and lagoonal silts, is probably truncated by the present surface around the salt domes and is possibly truncated throughout its extent. The next older formation, the Lissie sand and gravel (Pleistocene), is undoubtedly truncated by the surface represented by the present-day interfluves and perhaps also by the basal Beaumont surface. All outcropping older marine formations are, of course, truncated by the present upland surfaces as well as by certain unconformable surfaces within the overlying geologic section. The original landward margins of practically all the pre-Lissie groups and series have been removed long since, probably by several cycles of fluvial erosion. Even though the Beaumont strata were entirely conformable to the present surface and therefore not truncated by erosion, the same cannot be true of the underlying Lissie formation. That portion of the western Gulf Coastal Plain which may conceivably be a true depositional plain is thus seen to be only a narrow strip of land near the Gulf of Mexico. It is likewise apparent that there have been a great number of possibilities for stream capture, lateral migration, and other changes. And any one of these might make the traditional "hypothetic-genetic" use of the terms "consequent" and "subsequent" an oversimplification and unjustifiable distortion of the natural process.

Although it seems to have direct bearing on the ideas of Walther Penck, von Engeln nowhere mentions the significance of the Kettleman Hills anticline in Kings County, California. This anticline is evidently in a second or higher-numbered cycle of erosion, and yet beds of Pleistocene age have been tilted to more than 45°. This movement apparently is even yet in progress, as it has been reported that oil-well pipe has repeatedly been broken by a slow movement along some of the faults in the range.

"Insequent" streams and valleys are traditionally defined. A close study of the drainage in plains regions, however, will probably show that there are not so many such valleys as was formerly believed, except, perhaps, in badlands. The aligning influence of wind effects, insolation, and perhaps other processes, inherited from a former cycle of erosion or deposition, must be very common.

As for "Slopes Climatically Conditioned," this reviewer's casual experience would indicate that north-facing slopes in North Temperate and Arctic latitudes are prevailingly steeper than south-facing slopes, rather than the reverse, as stated by von Engeln on page 143. The explanation would seem to lie in the ratio between slope retreat and valley deepening.

Chapter xiv, dealing with the geomorphic effects of rock weathering, is good but too brief for a textbook in geomorphology. Very few geologists have given sufficient attention to strictly surficial processes. Certain geographers have recently stepped ahead in this study.

Another weakness is that, throughout the discussion of the peneplain and the cycle of erosion, practically no attention is given to the regional profile, projected or otherwise. This is a fault, for no other way to present much of the evidence for these concepts has yet been invented.

There is no adequate discussion of sand dunes. Neither windrift, shrub-coppice, nor source-bordering dunes are mentioned; and the concept of simple and complex dune forms is not presented. A reader could easily assume that all dunes are found in deserts.

Details of flood-plain topography are largely ignored as if they were too transitory to be worth the geomorphologist's attention.

Some of the faults of the book are the result of space limitations; yet, in spite of them all, the book is excellent. The careful manner in which evidence is presented both for and against certain controversial theories will be a source of satisfaction to experienced geological readers. This reviewer no less than others is indebted to Professor von Engeln for the carefully balanced discussions and for the elaborate array of definitions and terms, the original sources of which are all too scattered and difficult of access. The volume is well printed and contains many excellent photographs and three-dimensional diagrams. The Bibliography is convenient but unfortunately not so complete, even for recent years, as could be desired.

F. A. MELTON

Oil and Gas in Middle Tennessee. By KENDALL E. BORN. Nashville: State of Tennessee Department of Conservation, 1943. $0.25.

This is a single sheet comprising a map of the oil and gas pools of Middle Tennessee by physiographic provinces (scale 1 inch = 15 miles), the generalized columnar section from the beginning of the Ordovician to the top of the Pottsville, a table of oil and gas data, and a brief history of oil and gas development in the state. The provinces mapped are a part of West Tennessee, the Highland Rim, Central Basin, Cumberland Plateau, and the border of East Tennessee. The columnar section includes columns giving producing horizons, lithology, and areal distribution. A surprising amount of information is brought together on this very practical chart.

R. T. C.

Oil Well Drainage. By STANLEY C. HEROLD. Stanford University: Stanford University Press, 1941. Pp. xiii+407. $5.00.

This volume represents an application of the author's *Analytical Principles of the Production of Oil, Gas, and Water from Wells*, published in 1928. The earlier book presented a mathematical theory of oil-well drainage; the present volume seeks to apply these principles to actual practice. The author previously divided producing wells into three kinds: hydraulic control, volumetric control, and capillary control. In terms of the drainage of the corresponding reservoirs the author combines hydraulic and volumetric controls into one group, and capillary control into another. These two groups are referred to, respectively, as the "Cenozoic type of production and drainage" and the "Paleozoic type of production and drainage." This latter classification is based on the author's thesis that the older producing horizons are in capillary control, whereas the younger reservoirs display volumetric or hydraulic control. There are some exceptions, apparently, and Mesozoic reservoirs may be of either type. The author, in his Introduction, gives some twenty-one distinguishing characteristics of these types of production.

After introducing the two types of drainage, Herold considers a number of features of well or reservoir performance, including such topics as reservoir energy; the function of gas; radius and area of drainage; drainage across property lines; effect of multiple zones on drainage; effects of rates of production on drainage; etc. Each of these subjects is treated in terms of similarities and differences displayed by the two types of drainage. In each instance numerous examples are cited to illustrate the principles brought out.

In the interval between the author's two volumes tremendous advances have been made in the understanding of the behavior of reservoirs and individual wells. Perhaps the most widely accepted principles are those described by Muskat in his now classic volume. It is perhaps noteworthy that Herold apparently makes no explicit reference to these theoretical developments beyond pointing out in an appendix to his volume that "the mathematical theory known as 'hydrodynamics' is being applied to the control of well performance with some degree of success."

The typography and format of Herold's book are both pleasing, and the reader is helped by the marginal notations which summarize the contents throughout.

W. C. KRUMBEIN

Basic Principles of Weather Forecasting. By VICTOR P. STARR. New York and London: Harper & Bros., 1942. Pp. xxvi+299; figs. 125. $3.00.

The title of this book suggests a broad discussion of the theoretical bases of forecasting weather. Its author, however, appears to hurry with almost unseemly speed through the eighty pages occupied by the first three chapters (entitled, in order, "Forecasting the Field of Motion in the Atmosphere," "Forecasting the Actual Weather from the Field of Motion," and "Charts and Equipment for Short-Period Forecasting"), to which alone the title of the book is appropriate. He seems eager to get the "principial" part of his book out of the way and to move on to his exhibition, in the ensuing six chapters, of forecasting procedures followed at an up-to-date weather station. In these later chapters he permits the reader to look over the shoulder, and to a certain distance into the mind, of the forecaster as he works and to learn as much as he can without asking questions.

Like most demonstrations of craftsmanship, this one fails to convey to the reader all the insights, to say nothing of the skills, that guide the hand and mind of the practitioner. Insights into the theory that underlies the most advanced forecasting techniques are to be gained

only by absorbing the contents of many other writings, particularly those that have been published as the "Miscellaneous Reports of the Institute of Meteorology of the University of Chicago." The associated skills can, of course, be acquired only by practice.

Starr's book is therefore most useful to those who have followed the literature of American meteorology during the past few years. They will find in it a convenient summary of recent developments in method and a candid and reasonably full demonstration of new devices. As a textbook it is a useful adjunct to laboratory practice in the new methods but not a complete laboratory manual. Few of the readers of this *Journal* are in a position to make use of the book in either of these ways. It is to be recommended to them nevertheless; for if they look into it they may be stimulated to examine one of the most interesting phenomena of contemporary science in the United States. After a long period of stagnation, American meteorology for the second time is achieving world leadership. Starr's book is not a masterpiece that proves such leadership. It is merely evidence of what is happening in the places that count. The work of the active group to which its author belongs will soon render it obsolete. It is all the more valuable, therefore, as an interim report; as a milestone on the road along which the best American meteorologists are advancing too rapidly to pause, especially in wartime, to compose a more balanced and better-written treatise.

JOHN LEIGHLY

Hydrology. Edited by OSCAR E. MEINZER. ("Physics of the Earth," Vol. IX.) New York: McGraw-Hill Book Co. 1942. Pp. ix+712; figs. 155.

This comprehensive volume is the ninth in a series on the physics of the earth and represents the collaboration of some twenty-five authors, each of whom contributed a chapter or section of the book. Broad in scope, the volume covers the field of hydrology in a logical manner, following in general the course of the hydrologic cycle.

In his Introduction Dr. Meinzer outlines the scope of hydrology and traces the history of the science. Following the Introduction are two basic chapters on precipitation and evaporation. These are succeeded by chapters on the numerous processes of storage and transfer, ending essentially with the return flow of the water to the sea. Storage is covered in chapters on snow, glaciers, and lakes. These are followed by chapters on infiltration, transpiration, soil moisture, and ground water. A detailed chapter on runoff, which includes sections by nine authors, gives a comprehensive view of this subject. Droughts are briefly considered; a chapter on the physical changes produced by earth waters treats in part of soil erosion, the mechanics of rivers, and the chemistry of ground water. The last two chapters, on the hydrology of limestone and lava-rock terranes, are added as appendixes to the general organization of the volume, because of the special hydrological features of such terranes.

The organization of the several subjects in each chapter is logical and clear, and, despite the large number of contributing authors, the volume has a high degree of unity. In each instance the authors defined the basic terms and illustrated the principles with selected examples. Excellent graphs and charts supplement the text throughout.

The volume lives up to the high standards set by its predecessors. It is indispensable to specialists in any branch of hydrology as a source book covering the developments in other branches; it is indispensable to the general scientific reader for an over-all summary of this important branch of earth science.

W. C. KRUMBEIN

The Cretaceous Rocks of South India. By L. RAMA RAO. ("Lucknow University Studies," No. XVII.) Lucknow, 1942. Pp. 81; figs. 4.

The Cretaceous sedimentary rocks of South India appear only in scattered areas not far inland from the east coast. The most complete succession (from the Cenomanian to the Danian) is in the Trichinopoly District at the extreme south. The formations are highly fossiliferous, and a promising field for the study of Upper Cretaceous algae has been discovered.

R. T. C.